NIST

National Institute of Standards and Technology

Technology Administration

U.S. Department of Commerce

NISTIR 6603

January 2001

Electronics and Electrical Engineering Laboratory

Radio-Frequency Technology Division

Programs, Activities, and Accomplishments

The Electronics and Electrical Engineering Laboratory

Through its technical laboratory research programs, the Electronics and Electrical Engineering Laboratory (EEEL) supports the U.S. electronics industry, its suppliers, and its customers by providing measurement technology needed to maintain and improve their competitive position. EEEL also provides support to the federal government as needed to improve efficiency in technical operations, and cooperates with academia in the development and use of measurement methods and scientific data.

EEEL consists of five programmatic divisions, two matrix-managed offices, and a special unit concerned with magnetic metrology:

- Electricity Division
- Semiconductor Electronics Division
- Radio Frequency Technology Division
- Electromagnetic Technology Division
- Optoelectronics Division
- Office of Microelectronic Programs
- Office of Law Enforcement Standards
- Magnetics Group

This document describes the technical programs of the Radio-Frequency Technology Division. Similar documents describing the other Divisions and Offices are available. Contact NIST/EEEL, 100 Bureau Drive, MS 8100, Gaithersburg, MD 20899-8100, Telephone: (301) 975-2220, On the Web: www.eeel.nist.gov

The Cover symbolizes the diverse programs of the Radio-Frequency Technology Division and the cross section of industry that it serves. The programs range from the development of new metrology for microelectronics devices and circuits for radio and high-speed digital applications, to the precise characterization of electromagnetic fields, wireless systems, and antennas for radar and for satellite and terrestrial communications.

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U.S. DEPARTMENT OF COMMERCE
Norman Y. Mineta, Secretary

Technology Administration
Dr. Cheryl L. Shavers, Under Secretary of Commerce for Technology

National Institute of Standards and Technology
Karen H. Brown, Acting Director

Contents

Welcome

The Radio-Frequency Technology Division is a critical national resource for a wide range of customers. U.S. industry is the primary customer for both the Division's measurement services and for technical support on the test and measurement methodology necessary for research, product development, manufacturing, and international trade. The Division represents the U.S. in international measurement intercomparisons and standards development related to radio-frequency and microwave technology and electromagnetic fields. The Division also provides measurement services and expert technical support to other agencies of the Federal government to support their programs in domestic and international commerce, in national defense, in transportation and communication, in public health and safety, and in law enforcement.

This book will describe our many and diverse projects. However before you begin, I would like to briefly describe our mission, our programs, and our organization.

Mission

To provide the national metrology base for characterization of the electromagnetic properties of components, materials, systems, and environments, throughout the radio spectrum.

Division Function

The Division:

- Enhances national competitiveness by providing metrology resources to facilitate development and commercialization of a broad range of radio-frequency electronic and electromagnetic technologies;
- Develops theory, techniques, systems, and standards for measurement of electromagnetic and other essential properties of components, materials, environments and systems throughout the radio spectrum;
- Provides for national and international measurement harmony and formal traceability via calibration services, reference standards, and measurement intercomparisons;
- Disseminates research results via archival publications, conference presentations, workshops, courses, and external interactions. Programs typically address fundamental measurement problems that are of interest to a broad industrial cross-section and of sufficient difficulty that resources are generally not available elsewhere to solve them. Programs leverage internal resources with resources from other government agencies, industry and academia, and endeavor to meet the most critical industrial and governmental needs.

Our Technical Programs

The Division carries out a broad range of technical programs focused upon the precise realization and measurement of physical quantities throughout the radio spectrum. Key directions include: (a) the development of artifact reference standards, services and processes with which industry can maintain internationally recognized measurement traceability, (b) the advancement of technology through the development of new measurement techniques that are theoretically and experimentally sound as well as relevant and practical, (c) the assessment of total measurement uncertainties, and (d) the provision of expert technical support for national and international standards activities. We strive to perform leading-edge research in metrology of high quality that is responsive to national needs. The radio-frequency spectrum ranges from above audio to below the far-infrared. The programs range from measurements for microelectronics devices and circuits for radio and high-speed digital applications, to the characterization of electromagnetic fields, wireless systems, and antennas for radar and for satellite and terrestrial communications.

Division programs cover the following technical areas:

Fundamental Microwave Quantities
The Fundamental Microwave Quantities Program develops standards and methods for measuring impedance, scattering parameters, attenuation, power, voltage, thermal noise, and provides essential measurement services to the nation.

High-Speed Microelectronics
The High-Speed Microelectronics Program develops on-wafer measurement techniques for the radio-frequency electromagnetic characterization of microelectronic structures and devices.

Electromagnetic Properties of Materials
The NIST Electromagnetic Properties of Materials Program develops theory and methods for measuring the dielectric and magnetic properties of bulk and thin-film materials throughout the radio spectrum.

Wireless Systems
The Wireless Systems Program has three thrusts: the characterization of the nonlinear properties of devices and circuits, the proactive development of standards for broadband wireless access, and the characterization of passive inter-modulation products.

Antenna and Antenna Systems Metrology
The Antenna and Antenna Systems Program develops theory and techniques for measuring the gain, pattern, polarization of advanced antennas, for measuring the gain and noise of large antenna systems, and for measuring radar cross section.

Electromagnetic Compatibility

The Electromagnetic Compatibility Program develops theory and methods for measuring electromagnetic field quantities and for characterizing the emissions and susceptibility of electronic devices and products.

Division Organization

The Division is organized into two Groups that are focused upon measurements for guided-wave technologies and free-space electromagnetic-field technologies. The Groups and their managers are:

RADIO-FREQUENCY ELECTRONICS GROUP : Conducts theoretical and experimental research to develop basic metrology, special measurement techniques, and measurement standards necessary for advancing both conventional and microcircuit guided-wave technologies; for characterizing active and passive devices and networks; and providing measurement services for power, noise, impedance, material properties, and other basic quantities.

Group Leader: Robert Judish
Tel: 303-497-3380
Email: judish@boulder.nist.gov

RADIO-FREQUENCY FIELDS GROUP : Conducts theoretical and experimental research necessary for the accurate measurement of free-space electromagnetic field quantities; for characterization of antennas, probes and antenna systems; for development of effective methods for electromagnetic compatibility assessment; for measurement of radar cross section and radiated noise; and provides measurement services for essential parameters.

Group Leader: Andrew Repjar
Tel: 303-497-5703
email: repjar@boulder.nist.gov

The Division is also exploring new directions for the advancement of wireless technology via the proactive development of standards for broadband wireless access (BWA).

IEEE WIRELESS STANDARDS PROGRAM
Director: Roger Marks
Tel: 303-497-3037
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We hope that this collection of information will provide a useful resource for understanding the work of the Division and for making use of the technical capabilities and services that we provide for industry, government, and academia. We also invite you to visit our web site at: http://www.boulder.nist.gov/div813/. This site will provide you with more information on our projects as well as measurement-related software and publications that can be downloaded.

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Radio-Frequency Technology Division

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3132 LYONS, Ruth Marie, Secretary
3037 MARKS, Roger, Wireless Standards
3813 ANDRUSKO, Gaynel K., Admin. Officer
3514 GLAZE, Terry, Admin. Asst.

Radio-Frequency Electronics Group (813.01)

3380 JUDISH, Robert M. (GL)
5755 RIVERA, Susie A., Secretary

Power & Voltage Standards

3609 FREE, George (PL)
4133 CROWLEY, Tom
3264 ONDREJKA, Connie L.
3939 SHERWOOD, Glenn V.
3365 VORIS, Paul G.
5778 CLAGUE, Fred (GR)

Network Analysis

5362 JUROSHEK, John R. (PL)
3634 GINLEY, Ronald A.
5533 GROSVENOR, John H.
3210 LeGOLVAN, Denis X.
5249 MONKE, Ann F.
5231 PACKER, Marilyn

Noise Standards

3150 RANDA, James (PL)
5737 BILLINGER, Robert L.
5958 GROSVENOR, Chriss A.
3280 TERRELL, Andy

Non-Linear Device Characterization

7212 DeGROOT, Donald C. (PL)
3596 JARGON, Jeffrey A.
3652 REMLEY, Kate
5089 GUPTA, K.C. (GR)

High-Speed Microelectronics

3138 WILLIAMS, Dylan (PL)
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5490 WALKER, David K.

Electromagnetic Properties of Materials

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5491 KAISER, Raian K.
3656 JANEZIC, Michael D.
5752 RIDDLE, Bill F.
3997 KABOS, Pavel (GR)

Measurement Services

3753 DeLARA, Puanani L.

Radio-Frequency Fields Group (813.02)

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3321 HAAKINSON, Edit H., Secretary

Near Fields Antenna Techniques

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3863 GUERRIERI, Jeffrey J.
3471 MacREYNOLDS, Katherine
3927 STUBENRAUCH, Carl F. (GR)
3694 TAMURA, Douglas T.

Standard EM Fields and Transfer Probe Standards

3214 CAMELL, Dennis G.
3737 JOHNK, Robert T.
3756 MASTERSON, Keith D.
3168 NOVOTNY, David
5305 WEIL, Claude
3406 WILSON, Perry

EMC Measurements & Facilities

3995 CAVCEY, Kenneth H.
3472 HILL, David A. (GR)
6184 HOLLOWAY, Chris
5766 KOEPKE, Galen H.
5372 LADBURY, John

Antenna Systems Metrology

3603 MUTH, Lorant A.
3326 WITTMANN, Ronald C.

GL – Group Leader

PL – Project Leader

GR – Guest Researcher

PREP – Professional Research Experience Program Student

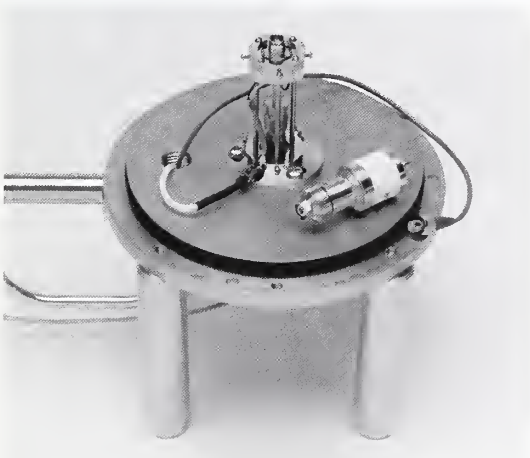
Tel. Numbers are (303) 497- xxxx (extension shown)

Fundamental Microwave Quantities

Power and Voltage

Project Goals

Develop, maintain, and improve standards, systems, and methods for measuring power over the frequency range from 100 kHz to 400 GHz. Develop, maintain, and improve standards, systems, and methods for measuring voltage over the frequency range from 10 kHz to 1 MHz. Provide measurement services and support to U.S. industrial and government laboratories.



2.4 mm microwave calorimeter and detector.

Customer Needs

A system's output power level is frequently the critical factor in the design, and ultimately the performance, of almost all RF and microwave equipment. Accurate measurements of power and voltage allow designers and users of measuring and test equipment to determine if performance specifications are met. Inaccurate measurements lead to over-design of products, and hence, increased costs. Economic gains are realized through improvements in accuracy. In a broad range of industries, there is a need for state-of-the-art calibration services so that customers can maintain quality assurance programs in the manufacture and distribution of their products. The availability of these services allows the customers to be competitive globally. The increasing speed of the internet, wireless technology, and FCC regulations on interference are driving the need for power measurements above 100 GHz. High bit-rate digital communications require the broadband characterization of microwave and millimeter-wave signals into and out of optoelectronic components. This characterization requires broadband power measurements from dc to 400 GHz.

Technical Strategy

The microwave industry is rapidly expanding into frequencies above 50 GHz. In response to this, we are developing new coaxial power standards and measurement capabilities. We now have a measurement capability for 2.4 mm coaxial power detectors over the range from 0.05 to 50 GHz. In addition to operating at higher frequencies, the 2.4 mm standard offers reduced uncertainty for power measurements. The 2.4 mm detector is also used as a standard to provide calibration services in other, lower frequency connector sizes.

MILESTONE: By 2001, investigate the calorimetric effective efficiency of the mounts at dc, where an absolute measure of the power into the calorimeter can be determined.

MILESTONE: By 2001, investigate the low-frequency 1 kHz to 50 MHz behavior of the microcalorimeter measurement of effective efficiency.

The 0.05 to 50 GHz direct-comparison measurement system provides state-of-the-art power measurement capability. The new system is faster and more accurate than any other system currently available. The measurement system replaces the need for multiple standards and measuring systems that are now needed to calibrate power standards over this frequency range. The Department of Defense calibration and standards laboratories require state-of-the-art systems to support their measurement requirements. Historically, NIST has provided these systems and continues to support the calibration activities of the Air Force, Army, and Navy Primary Standards Laboratories.

MILESTONE: By 2001, complete the construction of the direct-comparison power systems for the Air Force and Army Primary Standards Laboratories. These systems provide power calibration services over a frequency range of 0.05 to 50 GHz in GPC-7, Type N, 3.5 mm, 2.92 mm, and 2.4 mm coaxial transmission lines.

Technical Contacts:
John Juroshek
George Free

Staff-Years:
3.0 professionals
4.5 technicians

Funding Sources:
NIST (20%)
Other (80%)

Parent Program:
Radio-frequency

"I believe that the high speed communications lightwave market will finally be the business driver to open up the 50 to 200 GHz marketplace."

Doug Rytting
Agilent Technolcoies

MILESTONE: By 2002, evaluate and deliver a 0.05 to 50 GHz. direct-comparison power calibration systems to the Air Force and Army Primary Standards Laboratories.

Foreign National Measurement Institutes in developing industrial countries seek NIST support in establishing measurement capabilities. Microwave power is a fundamental quantity and is needed for determining other microwave quantities. NIST facilitates world-wide harmonization by providing support to developing nations.

MILESTONE: By 2001, deliver, make operational, and instruct in the operation of a state-of-the-art Type N microcalorimeter to the Singapore Productivity and Standards Board.

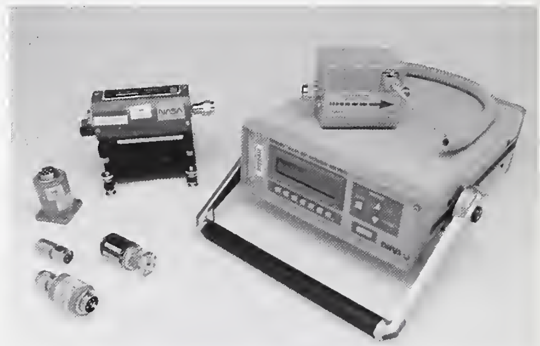
An important component in maintaining the units of RF power and voltage at NIST is participation in international comparisons. Through this link to the international community, NIST ensures that its capabilities in the measurement of power and voltage and the units that are maintained are comparable to those of other National Measurement Institutes. This relationship insures that the users of NIST calibration services will be able to compete in the international market.

MILESTONE: By 2001, complete the measurements and data analysis and send to the pilot laboratory the results of the determination of effective efficiency for two 3.5 mm thermocouple power standards measured over the frequency range 0.05 to 50 GHz.

Besides the need to measure power over an expanding frequency range, there is a need for calibrations of power standards at higher power levels. NIST has developed a high-power measurement system at power levels from 10 to 1000 watts for the frequency range 10 MHz to 1 GHz. The high-power standards are quite cumbersome, and ideally, all measurements needed for calibration should be done on a single system. The integration of additional instrumentation will allow for the various reflection coefficients needed for the calibration to be done in situ. It will also allow for the determination of the calibration factor at both ports of the power standard.

MILESTONE: By 2001, complete the analysis of the power measurement system necessary to report the calibration factor at both the input and output ports of high-power standards.

The Department of Defense has looked to NIST for guidance on microwave metrology issues and for ways to improve their measurement capabilities. One of the major problems facing the Department of Defense Primary Standards Laboratories is the development of a database for storing and verifying scattering parameter and power measurement data. NIST is currently in the process of developing a software package for storing and verifying measurements of scattering parameter and power for the Military Laboratories.



Microwave power meter and detectors

MILESTONE: By 2002, complete the development of an online software package for storing and verifying scattering parameter and power measurements for the Army Primary Standards Laboratory.

Voltage standards in the range 1 to 200 volts, and in the frequency range 100 kHz to 100 MHz serve as a basic testing tool for many manufacturers and users of RF instrumentation. The NIST calibration service and standards to support these measurements have been active for approximately forty years. The NIST primary standards were initially calibrated at the start of service. Since that time, although there have been numerous comparisons with other standards both domestic and international to insure their stability, the primary standards have not been internally recalibrated. Using state-of-the-art ac and dc sources, and with some redesign of the measurement circuitry, the uncertainties in these measurements will be reduced.

MILESTONE: By 2001, complete the intercomparison of NIST standards from 100 kHz to 100 MHz and reevaluate the calibration uncertainties.

There is an increasing demand for millimeter-wave calibration services, particularly at frequencies above 50 GHz. This demand is being driven to a large extent by the high bit rate digital systems that are currently being developed for optical fiber communications systems and the Internet. The present WR-10 waveguide calibration service is limited to a narrow frequency range in which RF sources are available. However, the existing microcalorimeter and WR-10 transfer standards operate over the frequency range 75-110 GHz. A few commercial wide-band sources (backward wave oscillators) are now becoming available on the market.

MILESTONE: By 2001, investigate available wide-band sources and purchase a source to cover frequency range 75 to 110 GHz for the WR-10 microcalorimeter.

MILESTONE: By 2001, incorporate a wide-band source in the WR-10 measurement system and evaluate available power sensors over the frequency range 75 to 110 GHz.

Due to the increasing speed of circuitry and communications, the high-frequency content of digital signals, and FCC regulations on harmonic emissions from radar and transmission devices there is a need for power measurements above 110 GHz. Digital signals pose constraints on measurements different from those of sinusoidal signals. Because circuits are becoming more integrated on a single chip, on-wafer power measurements are needed. An approach for meeting these needs must be developed. Extension of traditional measurement techniques as well as completely new approaches will be investigated.

MILESTONE: By 2001, develop a plan for meeting these needs with new power measurement services.

Accomplishments

- The evaluation of all NIST 2.4 mm primary standards in the microcalorimeter has been completed and a calibration history is being developed.

- Developed an improved and expanded calibration service for 3.5 mm power detectors. The new service uses the NIST direct-comparison system and some recently developed dc to 50 GHz thin film detectors. The 3.5 mm calibration service covers a frequency range of 0.05 to 33 GHz. In addition to offering lower uncertainties, the new service offers calibrations at finer frequency increments and coverage at higher frequencies than were previously available. A duplicate of this calibration capability was also implemented for the Navy Primary Standards Laboratory in San Diego, CA.

- A new calibration service has been developed for thermoelectric power detectors in Type N (0.05 to 18 GHz) and 2.4 mm (0.05 to 50 GHz) connectors.

- NIST participated in a key international comparison in coaxial power measurements with GPC-7 and Type N connectors that cover the frequency range from 1 to 18 GHz. This comparison, which is still in progress, will evaluate the measurement consistency of eight national laboratories.

- A new Type N microcalorimeter that covers the frequency range from 50 MHz to 18 GHz has been designed and constructed and is in the process of final evaluation. It measures effective efficiency over the frequency range 50 MHz to 18 GHz. This microcalorimeter differs from an earlier NIST model in that the thermopile has been redesigned using Peltier units in the thermopile instead of the traditional thermocouples units to give greater sensitivity to temperature change. The increased temperature sensitivity led to the discovery of other problems in the initial design. These problems have been solved and the microcalorimeter is now being used for the calibration of NIST and customers' primary standards.

- A second Type N microcalorimeter, identical to that mentioned above, has been completed for the Singapore Standards and Productivity Board. This measurement system has been shipped to Singapore for use as a primary power standard in their national laboratory.

- The measurement capability of the high-power calibration system (which measures power up to 1 kW in the frequency range from 2 to 1000 MHz) has been extended to measure the reflection coefficient of the source and the input and output of the power standard being calibrated. This was accomplished by incorporating a low-frequency network analyzer within the measurement system. A NIST Technical Note describing the system and the calibration service has been published.

- The international comparison, GT-RF/97-2, of power in WR-22 (33 to 50 GHz) has been completed. We were the pilot laboratory and have written a report describing the methodology and the results of the comparison.

- Documentation for the automated high-frequency voltage calibration system, which measures voltage from 1 to 7 V over the frequency range 100 kHz to 1000 MHz, has been completed.

- The micropotentiometer system, which measures voltage between 1 mV and 0.4 V over the frequency range 0.1 to 1000 MHz, has been automated but not as yet fully evaluated. The measurement time has been reduced by a factor of 10 or more.

- We have completed our measurements as part of an international comparison of voltage (GT-RF 92-6) over the frequency range from 1 to 1000 MHz. Our results have been sent to the pilot laboratory.

FY Deliverables

Calibrations

Calibrated 149 devices, which generated an income of $372,708.

Recent Publications

Juroshek, J. R.; NIST 0.05-50 GHz Direct Comparison Power Calibration System; Proc., Conf. on Pree. Electromagn. Meas., 14-19 May 2000, Sydney, Australia, pp. 166-167; May 2000

Allen, J. W.; The Switched Coupler Measurement System for High Power RF Calibrations; NIST TN 1510; July 1999

Allen, J. W.; Clague, F. R.; Larsen, N. T.; Weidman, M. P; The NIST Microwave Power Standards in Waveguide; NIST TN 1511; February 1999

Allen, J. W.; NIST's Switched Coupler High Power Measurement Service; Proc., Meas. Sci. Conf., 28-29 January 1999, Anaheim, CA, pp. 116-119; January 1999

Juroshek, J. R.; A Direct Calibration Method for Measuring Equivalent Source Mismatch; Microwave J., pp. 106-118; October 1997

Fundamental Microwave Quantities

Scattering Parameters and Impedance

Technical Contacts:
John Juroshek
George Free

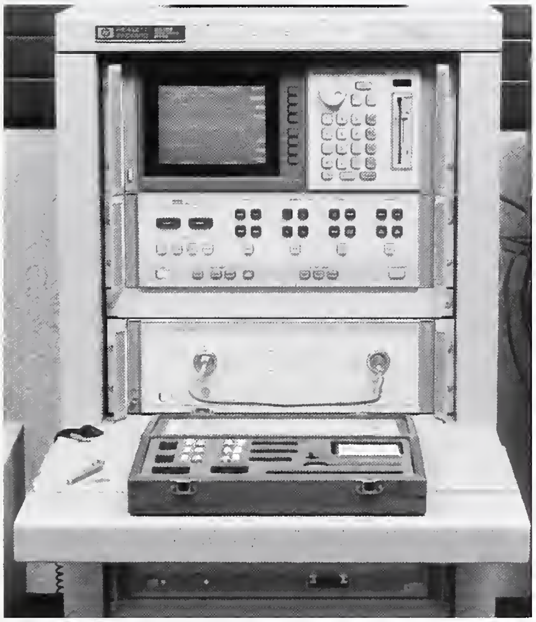
Staff-Years:
1.0 professionals
2.0 technicians

Funding Sources:
NIST (40%)
Other (60%)

Parent Program:
Radio-frequency

Project Goals

Provide traceability for microwave measurements in scattering parameters, impedance, and attenuation. Support the microwave industry by developing standards and new measurement techniques. Develop methods for assessing and verifying the accuracy of vector network analyzers.



Commerical vector network analyzer

Customer Needs

Vector network analyzers (VNAs) are the single most important instrument in the microwave industry. These instruments are commonly found on production lines, in calibration laboratories, and in research laboratories. Vector network analyzers are typically calibrated daily, the accuracy of their measurements can vary significantly after calibration depending on the operator's skill, the quality of the calibration standards, and the condition of the test ports. The microwave industry needs cost-effective techniques to monitor and verify the accuracy of VNA measurements. In addition industry requires validation of techniques and procedures they develop. NIST supports these needs by providing consultations on measurement techniques and uncertainty characterization. We also offer an extensive array of measurement services that allow VNA users to establish and gain confidence in their capability.

Technical Strategy

There is an increasing demand for millimeter-wave calibration services, particularly at frequencies above 50 GHz. This demand is being driven to a large extent by the high bit rate digital systems that are currently being developed for optical fiber communications systems and the Internet. NIST needs to develop improved and more cost-effective services in scattering parameters and power to support those needs.

MILESTONES: By 2002, improve calibration service in the 50 to 110 GHz frequency range. Develop the capability for continuous frequency coverage of scattering parameter and power measurements on the dual six-port network analyzers over WR-15 (50-75 GHz), and the WR-10 (75-110 GHz) frequency bands.

New connectors are being used for instrumentation and cables, as the communications industry develops applications at higher frequencies. Support is needed for these new connector interfaces.

MILESTONE: By 2003, add capability for calibration services in currently unsupported coaxial connector sizes (ie 1.85 mm, 1.0 mm, SMA and 75 ohm).

The Department of Defense's calibration and standards laboratories require state-of-the art systems to support their measurement capability. Historically, NIST has provided them with dual six-port vector network analyzers for scattering parameter measurements and direct-comparison systems for power calibrations. NIST will continue to aggressively support the calibration activities of the Air Force, Army, and Navy Primary Standards Laboratories.

MILESTONE: By 2001, complete construction of a 0.01 to 1000 GHz dual six-port network analyzer, and deliver to the Army Primary Standards Laboratory.

MILESTONE: By 2003, complete construction and refurbishment of the Navy 18 to 40 GHz dual six-port network analyzer.

The Department of Defense has looked to NIST for guidance on microwave metrology issues and for ways to improve methods for evaluating measurement data and for validating the calibration of complex instrumentation. Complex databases for storing and verifying measurements of scattering parameter and power are required. We are currently developing a software package for the Military Laboratories for storing and verifying scattering parameter measurements.

MILESTONE: By 2002, complete the development of an online software package for NIST and the Army Primary Standards Laboratory for storing and verifying measurements of scattering parametesr.

Our calibration customers have expressed concerns over the cost of our calibration services. Improvements in the measurement process for scattering parameters and impedances as well as the dimensional characterization of transmission-line standards are necessary to decrease measurements costs. Alternative measurement techniques that do not reduce the measurement uncertainty are being explored.

MILESTONE: By 2001, complete the uncertainty analysis of 14 mm and 7 mm transmission line dimensional characterization. Complete documentation for the dimensional measurement of airlines.

MILESTONE: By 2001, automate the calibration of coaxial resistance standards using LCR meters and calibrated standards and adaptors.

MILESTONE: By 2003, develop and implement improved and more cost-effective calibration procedures for vector network analyzers. Reducing calibration costs will ultimately result in faster turn-around times for NIST's calibrations and a reduction in the cost for those calibration services.

Accomplishments

- Developed a new measurement service, which allows customers to compare their VNA measurements with those made at NIST. Customers measure NIST transport standards with Type N and GPC-7 connectors and send the data to us. We analyze the data and issue a report on the comparison. The cost of this service is half that of our normal calibration service for scattering parameter standards.

FY Deliverables

External Recognition

Robert Judish was elected President of the Automatic Radio Frequency Techniques Group in December 1999.

Calibrations

Calibrated 200 devices, which generated an income of $186,218.

Recent Publications

GINLEY, R. A.; Microwave Network Analyzers: A Discussion of Verification Methods; Cal Lab, pp. 22-25; October 1999

JUDISH, R. M.; SPLETT, J.; Robust Statistical Analysis of Vector Network Analyzer Intercomparisons; Proc., IEEE Instrum. Meas. Tech. Conf., 24-26 May 1999, Venice, Italy, pp. 1320-1324; May 1999

GINLEY, R. A.; Microwave Network Analyzers - A Discussion of Verification Methods; Proc., Meas. Sci. Conf., 28-29 January 1999, Anaheim, CA, pp. 120-125; January 1999

JUROSHEK, J. R.; WANG, C. M.; McCABE, G. P.; Statistical Analysis of Network Analyzer Measurements; Cal Lab; May/June 1998

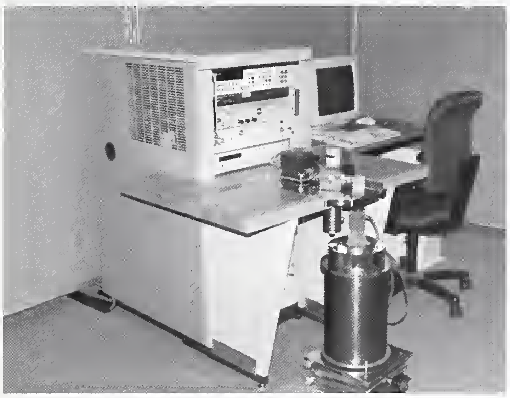
JARGON, J. A.; Revised Uncertainty of the NIST 30 MHz Phase Shifter Measurement Service; Proc., Meas. Sci. Conf., 5-6 February 1998, Pasadena, CA; February 1998

Fundamental Microwave Quantities

Noise

Project Goals

Develop methods for very accurate measurements of thermal noise; provide support for such measurements in the communications and electronics industries, as well as for other government agencies.



Noise figure radiometer and cryogenic standard

Customer Needs

Noise is a crucial consideration in designing or assessing the performance of virtually any electronic device or system that involves detection or processing of a signal. This includes communications systems, such as cellular phones and home entertainment systems, as well as systems with internal signal detection and processing, such as guidance and tracking systems or electronic test equipment. The global market for microwave and millimeter-wave devices in these areas is already huge and is undergoing explosive growth. Important trends that must be addressed include the utilization of higher frequencies, the growing importance of low-noise amplifiers, the demand for and lack of repeatable, traceable on-wafer noise measurement techniques, and the perpetual quest for faster, less expensive measurements. The two most important noise-related technical parameters requested by industry are the noise temperature of a one-port source and the noise figure of an amplifier.

Technical Strategy

In traditional (connectorized) noise temperature measurements and calibrations, the goal is to cover the frequency range from 1 to 75 GHz for waveguide sources, and 1 to 50 GHz in systems using coaxial connectors. Concurrently, redesign of the systems and test procedures is reducing the time required for such calibrations, thereby reducing the costs.

MILESTONE: By 2001, extend the 2.4 mm service up to 50 GHz. Reopen coaxial noise-temperature measurement services for 1 to 2 and 2 to 4 GHz. Rebuild system, rewrite software, and reopen measurement service for 30 & 60 MHz.

MILESTONE: By 2002, begin development of systems for frequencies above 65 GHz.

The second general thrust of the project is in amplifier noise figure measurements, where the goal is to develop cost-effective measurement services for amplifiers with coaxial connectors over the frequency range 1 to 18 GHz.

MILESTONES: By 2001, formalize noise-figure measurement techniques and write associated software. Analyze noise figure uncertainties. Offer a measurement or comparison service for amplifier noise figure for GPC-7 covering 8-12 GHz.

MILESTONE: By 2002, begin development of noise-parameter service for other bands.

The third major effort is to develop on-wafer noise measurement methods for characterizing devices and amplifiers in integrated circuits. This will be done first for noise temperature and subsequently for amplifier noise figure.

MILESTONES: By 2002, conduct an on-wafer noise-temperature round robin. Investigate on-wafer noise figure methods.

Central to all three of these efforts is the new noise-figure radiometer (NFRad) system, which was recently completed for 4 to 12 GHz. It has been designed to measure either one-port noise temperature or two-port amplifier noise figure, and it operates ten times faster than the previous NIST coaxial radiometers.

MILESTONE: By 2001, complete construction and testing of 1-2 and 2-4 GHz units.

MILESTONE: By 2002, complete testing of 12-18 GHz unit.

Technical Contact:
Jim Randa

Staff-Years:
2.0 professionals
2.0 technicians

Funding Sources:
NIST (60%)
Other (40%)

Parent Program:
Radio-frequency

"The on-wafer semiconductor device characterization is getting more and more important in the test and measurement world. Since new technologies now provide very low-noise devices, every improvement made in terms of accuracy is crucial and will have a real impact."

Ali Boudiaf
ATN Microwave

Accomplishments

- The new coaxial radiometer (NFRad) was completed and tested for 4 to 8 GHz and 8 to 12 GHz, and noise-temperature measurement services were reopened for these frequencies. NFRad is about ten times faster than the previous NIST coaxial radiometers. As a result the price for each additional frequency point in a coaxial calibration was reduced from $2147 in 1999 to $211 in 2000. The increased speed and exceptional repeatability and stability of the system will also allow the development of methods for accurate measurements of noise parameters of low-noise amplifiers. Design, operation, testing, and uncertainty analysis of the system were documented in a paper at the June 2000 ARFTG Conference and in a NIST Technical Note.

- Development of noise-temperature measurement capability in WR-22 waveguide (33-50 GHz) was completed, and the new noise-temperature measurement service was opened. Typical expanded uncertainties (2 sigma) for the new service are about 1.6 % to 1.7 % for noise temperatures from 1000 K to about 12,000 K. The WR-22 band is used for inter-satellite communications.

- After appropriate testing, the WR-90 noise-temperature measurement service was transferred from the old WR-90 Dicke radiometer to NFRad. NFRad allows continuous frequency coverage across the WR-90 band (8.2 to 12.4 GHz), whereas the old system could measure at only ten discrete frequencies. The transfer also results in increased accuracy in the measurements, as well as increased speed of calibrations, with a corresponding decrease in cost.

- Development of a new noise-temperature measurement service for 2.4 mm coaxial sources was completed and the measurement service was opened. The new service offers continuous coverage from 8 to 40 GHz, with the exception of one small gap. It is capable of measuring sources with noise temperatures from about 50 K to 15,000 K. Typical expanded ($k = 2$) uncertainties are between 1% and 1.4% up to 26 GHz and between 1.5% and 1.7% from 26.5 to 40 GHz, for a source with a noise temperature of about 5000 K to 10 000 K.

- A comparison was completed of three different methods for characterizing precision adapters. Several adapters were characterized with each method, the results agreed to within the estimated uncertainties, which ranged from about 0.002 to 0.012, depending on the method, connector, and frequency. Two papers were written reporting the results: one was presented at the 1999 IEEE MTT-S International Microwave Symposium and the other published in the IEEE Trans. on MTT.

- A set of measurements was performed and analyzed to test the stability of a noise source submitted by the Jet Propulsion Laboratory (JPL). By repeatedly measuring the noise temperature over the course of a week, we were able to measure the stability to within about 2 K (about 0.024%) per day, roughly 10 times better than we had promised. This success led to stability measurements on other types of noise sources, for periods of about one week and about one year. Results were presented at CPEM-2000 and in a paper to be published in IEEE Transactions on Instrumentation and Measurement.

- A combined effort by the Microelectronics and Noise Projects resulted in the design, fabrication, measurement, and characterization of prototype on-wafer noise sources. They were fabricated by the Microelectronics Project using on-wafer attenuator structures supplied by Cascade Microtech. The sources were tested and good results were obtained. The sources exhibit approximately constant noise temperatures and acceptably small reflection coefficients (≤ 0.12) across the frequency range measured (8 to 12 GHz). Two papers reported on this work: a short paper presented at the ARFTG conference in June 1998 and a full-length paper published in IEEE Transactions on MTT. New, improved sources have now been fabricated on substrates that include S-parameter calibration sets.

- The measurement service for the noise temperature of WR-15 waveguide noise sources for the frequency range 50 to 65 GHz was reopened. The service originally covered only 55 to 64.5 GHz and problems led to its closure about five years ago. To recertify the system, critical system checks were performed. The six-port reflectometer software was improved, the uncertainty analysis was checked and updated, and check standards were remeasured and compared to previous results. Typically expanded uncertainties (2 sigma) for the revived service are expected to be about 1.7 % for noise temperatures of 5000 K to about 12,000 K. The WR-15 band extends from 50 to 75 GHz.

"Thanks for the update on your thermal noise calibrations. It's really great news to us users that you are upgrading your capability and also reducing the calibration fees. Keep up the good work!"

Larry Tarr
Chief, Electrical Stds Lab
U.S. Army Primary Stds Lab

Principal applications in this band are cross-links between satellites around 60 GHz.

FY Deliverables

Calibrations

Calibrated 10 devices which generated an income of $71,415.

Recent Publications

J. Randa, L.P. Dunleavy, and L.A. Terrell, "Stability measurements on noise sources," IEEE Trans. Instrum. Meas., to be published (2000 or 2001)

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C. Grosvenor, J. Randa, and R.L. Billinger, "NFRad"Review of the new NIST noise measurement system," 55th RFTG Conference Digest, pp. 135-44; Boston, MA, (June 2000)

J. Randa, "Multiport noise characterization and differential amplifiers," 55st ARFTG Conference Digest, pp. 106-115; Boston, MA (June 2000)

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Randa, "Uncertainties in NIST noise-temperature measurements," JNIST Tech. Note 1502, (March, 1998)

J. Randa and L.A. Terrell, "Noise-temperature measurement system for the WR-28 band," NIST Tech. Note 1395 (August, 1997)

D.F. Wait and J. Randa, "Amplifier noise measurements at NIST," IEEE Trans. Instrum. Meas., IM-46, pp. 482-485, (1997)

J. Randa, "Noise temperature measurements on wafer," NIST Tech. Note 1390 (March, 1997)

High-Speed Microelectronics

Project Goals

High-Speed Microelectronics Metrology supports the telecommunications and computing industries through research and development of high-frequency on-wafer metrology. The goal of the project is to develop electrical metrology for new 40 GB/s optical links, 30 to 100 GHz wireless systems, high-speed microprocessors by establishing accurate on-wafer waveform, and frequency-domain metrology to 200 GHz.

Customer Needs

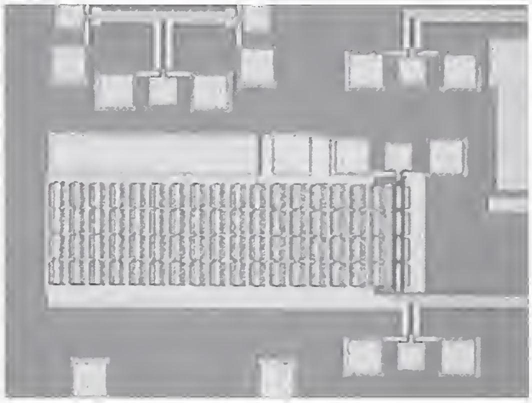
The rapid advance in the speed of modern telecommunications and computing systems drives this project. The explosion of optical and wireless telecommunications is fueling the demand for microwave and radio-frequency microelectronics. Advances in the silicon industry continue to drive the size of digital circuits down and their clock rates up to microwave frequencies. Characterizing a microprocessor with a 2 GHz clock rate requires at least 10 GHz of calibrated measurement bandwidth on lossy silicon substrates. Limited available bandwidth is pushing wireless systems into the millimeter-wave region of 30 to 100 GHz. New 40 GB/s optical links require electrical metrology to 200 GHz. However, current commercial sampling oscilloscopes are limited to a 50 GHz bandwidth and current broadband single-sweep network analyzers are limited to 110 GHz. These extraordinary advances in technology require new high-speed frequency-domain and waveform measurements.

Technical Strategy

Coaxial connectors pose insurmountable economic hurdles for high-speed telecommunications and computing. This project focuses on the only feasible alternative, developing high-speed on-wafer time-domain and frequency-domain metrology for highly integrated structures, differential transmission lines, and on-wafer devices. Due to their inherent high-speed and calculable systematic errors, electrooptic sampling systems play a central role in the project. We are using commercial oscilloscopes to establish accurate on-wafer waveform metrology to 50 GHz, using electrooptic sampling systems to break the 50 GHz waveform measurement barrier, and are working on the 110 GHz frequency-domain network analysis barrier.

MILESTONE: By 2001, build an electrooptic on-wafer waveform measurement system, and use the system to verify calibrations for commercial sampling oscilloscopes to 50 GHz.

MILESTONE: By 2001, apply oscilloscopes traceable to electrooptic sampling systems to on-wafer waveform measurements for digital silicon ICs.



Silicon waveform generator and high-impedance probe

MILESTONE: By 2001, establish measurements of absolute electrical phase traceable to electrooptic sampling systems to 50 GHz.

MILESTONE: By 2002, perform electro-optical on-wafer waveform measurements to 110 GHz. Apply to the characterization of 10 and 20 GB/s telecommunications components. Use calibrated oscilloscopes to measure waveforms in fast, differential-coupled silicon interconnect structures. Extend functional test of wireless communications components to 100 GHz.

MILESTONE: By 2003, extend on-wafer frequency-domain and waveform measurement capability to 200 GHz. Apply to the tesing of 40 GB/s telecommunications components.

Accomplishments

- Built an on-wafer electrooptic waveform sampling system that features several hundred GHz of measurement bandwidth and calculable systematic errors. This system will play an essential role in the program, providing both high-speed and traceability for our commercial sampling oscilloscopes.

Technical Contact:
Dylan Williams

Staff-Years:
2.0 professionals
1.0 technicians

Funding Sources:
NIST (80%)
Other (20%)

Parent Program
Radio-frequency

"We see that obtaining calibrated waveforms will be essential to designing state-of-the-art devices, circuits, and systems. Along with the design capability, there will be required new measurements extending to at least 200 GHz to support 40 GB/s telecommunciations links."

Doug Rytting
Agilent Technlogies

■ Fabricated twelve prototype waveform test chips at a silicon foundry. The chips feature unique integrated high-impedance probes that reduce the loading of the oscilloscope on the circuit. This prototype will demonstrate that we can perform a calibrated waveform measurement with 50 GHz bandwidth on the silicon chip, and transfer that waveform to another measurement system, while maintaining the integrity of the wavefront. The measurement method is also useful in its own right for directly testing high-speed silicon digital ICs.

■ Tested power monitors that will be part of a CMOS calibration chip with known voltages and currents. The chips will be used to calibrate instruments for an at-speed digital test. Sensitivity of power monitors is adequate for transferring voltages with 0.01V precision at 10 GHz.

"Two programs developed by NIST, MultiCal™ and Cap, enabled development of pre-matching networks with first-pass success, subsequently enabling my group to characterize transistors in a fashion which presently no other RF/MW company has."

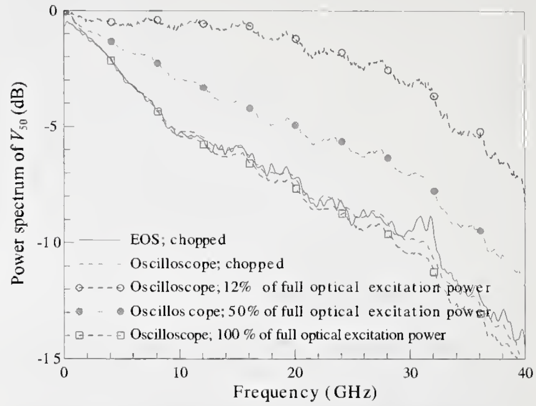
John Sevic
UltraRF

■ Developed an accurate method of measuring the characteristic impedance of a transmission line fabricated on lossy silicon substrates and an accurate on-wafer calibration based on the method.

■ Developed instrumentation and methods for accurately and completely characterizing small printed coupled lines. These lines are essential building blocks for printed high-speed interconnects.

■ Developed a causal microwave circuit theory whose voltages and currents reproduce the temporal behavior of the actual electric and magnetic fields in the circuit. The new causal theory does this by linking the time and frequency domains. This fixes all of the remaining free parameters of conventional microwave circuit theory, resolving one of the most troublesome dilemmas of microwave circuit theory in a unique and creative fashion. The theory provides an important theoretical foundation for our efforts to unify on-wafer waveform and frequency-domain measurements.

■ Characterized low-K dielectrics fabricated at SEMATECH using transmission-line methods developed at NIST. Measurements from different line geometries agreed to within 5% up to 40 GHz. The work involved tight collaboration between NIST and SEMATECH. The test structures were designed at NIST, the samples were fabricated at SEMATECH, the electrical measurements and data analysis were performed at NIST, and the physical measurements and electromagnetic analysis were performed at SEMATECH. This work provides needed confidence to the semiconductor industry in their drive to incorporate low-K materials in their products.



Comparison of electrooptic sampling system measurements to oscilloscope measurements

FY Deliverables

Software

MultiCal measurement software implementing the multiline TRL calibration.

Four-Port Measurement software for performing orthogonal two-port, three-port, and four-port measurement with in-line calibrations and inexpensive hardware.

Characteristie Impedance of Silicon Transmission Lines Software designed to accurately determine the characteristic impedance of transmission lines fabricated on silicon substrates.

CausalCat Software: For computing causal characteristic-impedance magnitude from the phase of the integral of the Poynting vector over the guide cross section.

Recent Publications

ARZ, U.; WILLIAMS, D. F.; WALKER, D. K.; ROGERS, J. E.; RUDACK, M.; TREYTNER, D.; GRABINSKI, H.; Characterization of Asymmetric Coupled CMOS Line; Dig., IEEE Microwave Theory Tech. Intl. Symp., 11-16 June 2000, Boston, MA, pp. 609-612; June 2000

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WILLIAMS, D. F.; DeGROOT, D. C.; Electrical Measurements for Electronic Interconnections at NIST; Proc., URSI General Assembly, Toronto, Canada, 13-21 August 1999, p. 31; August 1999

WILLIAMS, D. F.; ALPERT, B. K.; Characteristic Impedance, Power and Causality; IEEE Microwave Guided Wave Lett., Vol. 9, No. 5, pp. 181-182; May 1999

WILLIAMS, D. F.; ALPERT, B. K.; Characteristic Impedance, Causality, and Microwave Circuit Theory; Proc., IEEE Sig. Propagation Interconnects Workshop, 19-21 May 1999, Titisee-Neustadt, Germany, pp. 1-2; May 1999

WILLIAMS, D. F.; WALKER, D. K.; 0.1-10 GHZ CMOS Voltage Standard; Proc., IEEE Sig. Propagation Interconnects Workshop, 19-21 May 1999, Titisee-Neustadt, Germany; May 1999

WILLIAMS, D. F.; Metal-Insulator-Semiconductor Transmission Lines; IEEE Trans. Microwave Theory Tech., Vol. 47, No. 2, pp. 176-181; February 1999

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WILLIAMS, D. F.; High Frequency Limitations of the JEDEC 123 Guideline; Proc., Electrical Performance of Electronic Packaging., 25-28 October 1998, West Point, NY, pp. 45-49; October 1998

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WALKER, D. K.; WILLIAMS, D. F.; Comparison of SOLR and TRL Calibrations; Dig., 51st Auto. RF Tech. Group Conf., 7-12 June 1998, Baltimore, MD, pp. 83-87; June 1998

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WILLIAMS, D. F.; WALKER, D. K.; Lumped-Element Impedance Standards; Dig., 51st Auto. RF Tech. Group Conf., 7-12 June 1998, Baltimore, MD, pp. 91-93; June 1998

WILLIAMS, D. F.; Metal-Insulator-Semiconductor Transmission Line Model; Dig., 51st Auto. RF Tech. Group Conf., 7-12 June 1998, Baltimore, MD, pp. 65-71; June 1998

WILLIAMS, D. F.; WALKER, D. K.; In-Line Multiport Calibration; Dig., 51st Auto. RF Tech. Group Conf., 7-12 June 1998, Baltimore, MD, pp. 88-90; June 1998

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DEGROOT, D. C.; MARKS, R. B.; JARGON, J. A.; A Method for Comparing Vector Network Analyzers; Dig., Auto. RF Tech. Group Conf., 4-5 December 1997, Portland, OR, pp. 107-114; December 1997

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Wireless Systems

Nonlinear Device Characterization

Project Goals

Develop and support general methods of characterizing nonlinear devices, components, and circuits used in digital wireless communications; refine and transfer these methods through interactions with industrial research and development laboratories.

Dr. Kate Remley performs large-signal measurements of an RF power amplifier using the Nonlinear Network Measurement System.

Customer Needs

Radio-Frequency measurements are applied extensively in the deployment of commercial wireless communication systems. They are crucial to all stages of system development, from device modeling, to circuit design and system performance characterization. NIST's RF and microwave measurement support has recently expanded to address the critical need for accurate measurements of nonlinear electrical networks and to support industrial standards development.

Technical Strategy

The Nonlinear Device Characterization Project is focusing on the verification of model- and measurement-based descriptions of devices and circuits containing nonlinear elements, primarily RF power amplifiers. Traditional microwave circuit design has relied on the ability to cascade circuit elements through simple linear operations and transformations. When an RF circuit includes a nonlinear element, engineers lose the ability to predict circuit performance across operating environments or states. With the wireless revolution, many researchers have devoted their time to developing models of nonlinear devices that will work with existing computer-aided design (CAD) techniques. Others have worked on developing specialized and functional tests that show how nonlinear behavior might affect system performance. Presently, there is a critical need for fundamental RF measurement techniques to verify and validate these models and figures of merit. Contributions in this area will significantly improve design-cycle efficiency and trade between manufacturers, and will eventually facilitate improvements in communications through the full incorporation of nonlinear models at the system design level.

The project recently acquired and established a new measurement facility known as the Nonlinear Network Measurement System (NNMS). The system provides the most general approach to measuring large-signal responses. It is a stimulus-response network analyzer that supplies periodic signals then acquires broadband incident and reflection waveforms at the device under test. The NIST facility will be used as a reference system in measurement and model comparisons. The project team is developing accurate calibration and measurement techniques for the NNMS, including validation of the Nose-to-Nose calibration technique, the only practical method of measuring signal phase relations components with 50 GHz bandwidths. The project team is now refining the statement of measurement uncertainty in the Nose-to-Nose method and will apply it to the NNMS measurements.

MILESTONES By 2001, bound the measurement uncertainty of the Nose-to-Nose calibration; bound uncertainty in NNMS measurements; implement advanced OSLT calibration methods; develop user-friendly interface for the NNMS. By 2002, refine phase calibration uncertainty statement; add multiline TRL calibrations; add modulated signal stimuli; track changes in NNMS measurement uncertainty with impedance tuning.

Technical Contact:
Don DeGroot

Staff-Years:
3.0 professionals
1.0 guest scientists

Funding Sources:
NIST (90%)
Other (10%)

Parent Program
Radio-frequency

""Agilent Lightwave Division would like to encourage NIST's continued work to develop the nose-to-nose characterization, so that the technology can become more widely available."

Dennis Derickson,
Agilent Technologies

"Overall, I believe the [NIST] paper does an excellent job of outlining the [PIM] work ahead and summarizing the work to date. Implementing this more rigorous model is a significant step in understanding the behavior of PIM in cable assemblies."

Brad Deats
Summitek Instruments

"This and your previous paper do great justice to the [Nose-to-Nose] topic. I'm pleased the subject is getting the attention it deserves. Our original publication was both an introduction to the kickout notion and a plea for help for further development. Thank you for your efforts."

John Kerley
Agilent Technologies, Inc.

The Nonlinear Network Measurement System is being applied first to canonical circuits in order to compare general measurements with predictions made by commercial CAD simulators and new behavioral models. The goal is to develop a stable verification device that can be used in inter-laboratory comparisons. Second, the measurement system is being applied to develop and verify artificial neural network (ANN) models for nonlinear active circuits being developed in cooperation with the University of Colorado. NNMS data will be used to train ANN models, to verify circuit operation and model predictions, and to validate a circuit optimization approach.

MILESTONE: By 2001, develop portable models of a nonlinear verification device; conduct a measurement intercomparison using verification device; apply new modeling techniques to diode circuit design; develop generalized frequency-domain nonlinear models based on NNMS data; characterize a sample power amplifier and compare to advanced simulation results.

MILESTONE: By 2002, compare sparse tone and modulated signal characterizations of power amplifiers; apply new nonlinear measurement-based models to power amplifier design; simulate link between system performance and amplifier nonlinearity.

NIST has also been conducting research into passive sources of nonlinearity found in wireless communications base stations. Key industry representatives have requested NIST's participation in passive intermodulation measurements (PIM). The Nonlinear Device Characterization Project responded by establishing relationships with a working group of the International Electrotechnical Commission, which is developing PIM standards for connectors and cable assembly manufacturers. From this interaction, the project designed and conducted the first phase of a PIM measurement intercomparison. The study revealed the level of agreement achieved by the participants. A second phase of the inter-comparison is in progress.

MILESTONE: By 2001, conclude 2nd phase PIM intercomparison study.

Time-domain measurements form an interesting alternative to continuous-wave nonlinear device measurements. Presently, NIST is investigating full vector correction of a time-domain network analyzer system. These time-domain methods have been applied to linear passive networks up to 20 GHz, but they can be extended to enable broadband instrumentation for the millimeter-wave region.

MILESTONE: By 2002, Add multiline TRL calibrations to TDNACal software.

Accomplishments

- In response to requests by U.S. industry and members of the International Electrotechnical Commission (IEC), members of the Nonlinear Device Characterization Project conducted the first phase of the Passive Intermodulation Measurement Intercomparison for the U.S. Wireless Industry. While the study shows reasonable standard deviations about the expected mean values for most of the data sets, it reveals significant discrepancies reported by some participants and large standard deviations in other cases. This study is already enabling participating companies to improve their PIM measurement capabilities.

- Collaborated with the Intel Technical CAD (TCAD) Division to measure the behavior of high-speed digital transistors (MOSFETs) and to extract accurate device parameters. The key technological hurdles were the measurement of three-port devices when the three ports are connected in different metalization layers, and the high RF losses encountered in commercial CMOS technology. NIST personnel designed two sets of calibration standards for the three-port devices. Intel fabricated three generations of test wafers and worked with NIST in verifying the calibrations. This activity also relied on new software developed by the High-Speed Microelectronics Project to remove contact-pad effects. The new approach is being used by TCAD engineers to quantify device behavior with much higher accuracy.

- Developed a complete Open-Short-Load-Thru (OSLT) calibration for the NIST TDNACal software that implements equivalent circuit model descriptions. This new calibration is a significant enhancement to existing software, and for the first time, allows NIST to study measurement uncertainty in OSLT calibrations that make use of the equivalent-circuit model parameters. Presentation of this work at the 54th ARFTG Conference received the Best Paper Award.

- Characterized the accuracy of several proposed calibration techniques for microwave vector network analyzers (VNA). Project staff discovered significant errors in the proposed methods and introduced a new robust OSLT calibration method that offers demonstrably improved accuracy in four-sampler VNA measurements.

- In collaboration with Professor K. C. Gupta of the University of Colorado at Boulder, applied artificial neural networks (ANNs) to improve the modeling of on-wafer open-short-load-thru (OSLT) standards and coaxial line-reflect-match (LRM) calibrations used for calibrating vector network analyzers. The new methods will be used in TDNACal and new NNMS software.
- Discovered nonlinear error mechanism in the Nose-to-Nose calibration. Through an innovative combination of large-signal and small-signal analyses, showed how nonlinear junction capacitance in the sampler circuit induces an error that had been ignored in the initial Nose-to-Nose analysis.
- Initiated NIST's Nonlinear Network Measurement System (NNMS) and conducted NIST's first large-signal nonlinear device verification experiments. Agilent Technologies delivered the NNMS instrument in fulfillment of a custom equipment contract and extensive collaborative research effort with NIST.

FY Deliverables

Software

TDNACal: software designed for calibrated time-domain network analysis measurements.

External Recognition

Jeff Jargon received the Best Paper Award at the 54th ARFTG Conference for his presentation on OSLT calibrations.

Recent Publications

J. A. Jargon, K. C. Gupta, and D. C. DeGroot, "Artificial neural network modeling for improved on-wafer OSLT calibration standards," Int. J. RF Microwave Computer-Aided Engin., vol. 10, no. 5, pp. 319-328, Sep., 2000

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Wireless Systems

Standards for Broadband Wireless Access

Technical Contact:
Roger Marks

Staff-Years:
1.0 professionals

Funding Sources:
NIST (100%)

Parent Program
Radio-frequency

Project Goals

This project accelerates the development of the broadband wireless communications industry by leading and facilitating the open development of accredited, consensus technical standards for worldwide use.

Customer Needs

With the start of U.S. auctions in 1994, the radio spectrum has been moving into private hands. This spectrum is almost unregulated. Innovation has brought new technology to market but, without widely supported standards, costs remain unnecessarily high, exports are stifled, and the benefits of new technology fail to fully flow down to the consumer.

Technical Strategy

This project allows NIST to take a proactive role in the development of technically superior standards for wireless communications. Its current focus is on fixed broadband wireless access systems, which have the potential to provide competitive alternative connections to Internet, voice, and video networks for residential and business sites. Spectrum for these services is in private hands, but the widescale deployment of systems awaits standardization.

History and Progress of Standardization Effort

The project effort has been directed toward establishing and leading a global industry effort in broadband wireless access standardization. The project began when project leader Roger Marks launched a web site and newsletter (currently with over 850 subscribers) in April 1998. At a Kickoff Meeting in August 1998, Marks suggested that, based on his research, the most appropriate organization with which to pursue standardization would be the LAN/MAN [Local/Metropolitan Area Networks] Standards Committee of the Institute of Electrical and Electronics Engineers, Inc. (IEEE), a nonprofit technical professional society. The IEEE, through its accredited Standards Association, supports an open process for global standards development. The committee, informally known as IEEE 802, has become the world's primary (and virtually only) developer of standards for computer networking; its 802.3 Ethernet and 802.11 Wireless LAN standards are ubiquitous. Following a meeting, IEEE 802 initiated the temporary IEEE 802 Study Group on Broadband Wireless Access, and Marks was named Chair. The Study Group has met twice, attracting 97 participants from over 70 companies during meetings in January and March 1999. In March, IEEE 802 created the standing IEEE 802.16 Committee on Broadband Wireless Access and named Marks as Interim Chair. He was later elected (and then reelected) by unanimous vote of the membership.

The IEEE 802.16 committee, meeting bimonthly, has held 11 week-long sessions (in addition to several subgroup meetings). The group has three approved projects to develop air interface standards: for 10-66 GHz, for licensed bands from 2-11 GHz, and for unlicensed bands from 5-6 GHz. A fourth project is a recommended practice on coexistence, helping operators to avoid destructive interference. The group has 134 Voting Members, and over 500 people from 15 countries have attended at least one session. Session attendance has grown to over 200.

In accordance with IEEE 802 rules, Marks, as Working Group Chair, decides the Group's procedural issues while the Group makes the technical decisions. In addition, Marks leads Task Group 1, which handles the 10-66 GHz air interface. In according with the development plan he proposed, Task Group 1 began by considering 32 proposals at the November 1999 meeting. By May 2000, consensus on a unified proposal had been reached. A draft is being refined and expected to go to ballot in early 2001. The coexistence document was completed earlier and went to ballot in November 2000. The 2-11 air interface project aired 20 proposals in November 2000 and is scheduled to complete a draft in early 2002. The air interface for unlicensed frequencies, addressing the Unlicensed National Information Infrastructure (U-NII) bands, was handled in a Study Group through much of 2000 and approved as a project in December 2000.

Marks also maintains the 802.16 web site, which has served over 400,000 files in a calendar month. One air interface draft was downloaded over 20,000 times.

Marks also plays a role in broader issues of open standardization. He is involved in the IEEE Standards Association and has organized sessions at technical meetings exploring the role of standards in wireless communications. He is helping to organize the 2001 IEEE Conference on Standards and Innovation in Information Technology, set for Boulder in October 2001.

Wireless System Characterization Facility

One goal of the Wireless System Characterization Facility is to support standardization by providing unbiased measurement results. Another is to apply system-level measurement results to challenging component-level characterization issues, particularly for nonlinear components. Two Guest Researchers visiting from January-June 2000 carried out nonlinear measurements and simulations of a power amplifier suitable for use in systems supporting 802.16's 10-66 GHz air interface standard. The results were reported the 802.16.

FY Deliverables

External Recognition

Roger Marks was elected to a three-year term, beginning in 1999, on the Administrative Committee of the IEEE Microwave Theory and Techniques Society (MTT-S).

Roger Marks was recognized as an IEEE Fellow, class of 2000, for contributions in wireless communications standards and metrology.

Recent Publications

Marks, R. B.; The IEEEe 802.16 Working Group On Broadband Wireless; IEEE Network, Vol. 13, No. 2, pp. 4-5; March/April 1999

Marks, R. B.; Standards Make Wireless Work; Applied Microwaves And Wireless, pp. 101-102; February 1999

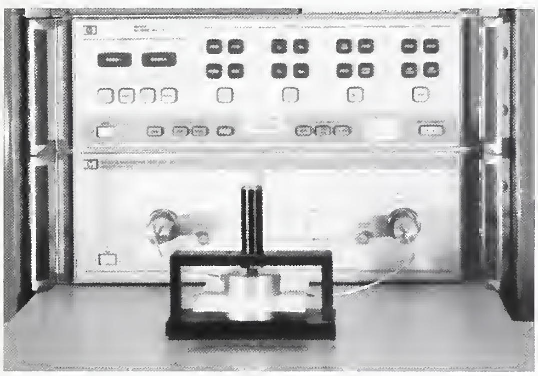
Marks, R. B., The National Wireless Electronic Systems Testbed And Its Initial Development; Private Cable And Wireless Cable, pp. 18-21; February 1999

Marks, R. B.; The National Wireless Electronic Systems Testbed and its Initial Development; Dig., Auto. RF Tech. Group Conf., 3-4 December 1998, Rohnert Park, CA, pp. 95-100; December 1998

Electromagnetic Properties of Materials

Project Goals

Develop, improve, and analyze measurement methods, uncertainty estimates, and theory for the characterization of the complex permittivity and permeability of dielectric and magnetic materials and thin films in the RF and microwave spectrum, as a function of temperature and bias fields. Develop models for underlying relaxation phenomena that occur in dielectric and magnetic materials. Provide measurement services and Standard Reference Materials (SRMs) to customers. Organize and implement measurement comparisons and interact with standards committees and workshops. Disseminate information through workshops, talks, NIST publications, and papers.



Measuring a PWB sample in the split cylinder resonator

Customer Needs

Thin films form the basis for microelectronic circuitry and substrate-based components. Industry requires new thin-film measurement methods with well-characterized uncertainties. Substrate electronic materials are widely used in industry for applications such as printed wiring boards (PWB), low-temperature cofired ceramics (LTCC), and microwave components. Dielectric and loss properties of ceramics substrates and crystals are crucial in the wireless and time standards arena. Hence critical needs exist for accurately characterizing the dielectric and magnetic properties of these materials. Computer-based design methods require very accurate data on the dielectric and magnetic properties of these materials over a wide frequency spectrum and temperature range. There is a particular need for small, nondestructive, dielectric resonators that can be used on-line to characterize test coupons or panels in LTCC and PWB manufacturing. Development of accurate methods for measuring frequency-agile ferroelectric substrate materials are also needed. These materials used needed in new phased-array antennas and other components. The Justice Department requires composite dielectrics that emulate the human body's electrical properties for use in metal detector testing. Theoretical models of dielectric and magnetic response are necessary for basic understanding of relaxation. Dielectric reference materials are needed to provide measurement traceability to NIST and measurement intercomparisons provide assessments of the quality of material characterization.

Technical Strategy

To satisfy the need for accurate thin-film measurement we are developing new transmission-line and resonator methods. We are also developing an uncertainty analysis for the transmission-line thin-film method.

MILESTONE: In 2001, perform measurements for customers of both patterned and unpatterned dielectric thin films using resonator methods. Evaluate uncertainties in these measurements.

We are developing improved resonator techniques and uncertainty characterization for substrates. These methods include the split-cylinder and split-post dielectric measurement methods.

MILESTONE: In 2001, improve the full-mode software for the split-post resonator and incorporate it into LABVIEW. Use the nondestructive resonator methods we developed in 2000 for measurements on LTCC materials.

To satisfy the need in the PWB and LTCC industries for accurate characterization of thin materials we are developing variable-temperature metrology and nondestructive methods for ultra low-loss dielectrics and substrates. In order to disseminate knowledge on substrate characterization we wrote an overview Technical Note on PWB measurements describing the various testing methods with measurement data; we are in the process of writing another Technical Note for LTCC measurement methods.

Technical Contacts:
Jim Baker-Jarvis

Staff-Years:
5.0 professionals
0.2 technicians
0.5 guest scientists

Funding Sources:
NIST (30%)
Other (70%)

Parent Program:
Radio-frequency

"This letter is to recognize the importance of the high frequency measurements performed at NIST for SEMATECH fabricated wafers... with low-k materials. The high frequency measurements performed at NIST... provide the effective dielectric constant up to 40 GHz.

Volker Blaschke and Bob Havemann
SEMATECH

"I would like to acknowledge the excellent work of the Electromagnetic Properties of Materials Project for recently working with Brad Givot on several measurements for 3M...This work was extremely valuable for determining the electrical permittivity for two important programs at 3M."

Dr. William Coyne
3M

MILESTONE: In 2001, measure an array of low-loss crystals, polymers, and ceramics that are important to our customers as a function of temperature and up to 100 GHz.

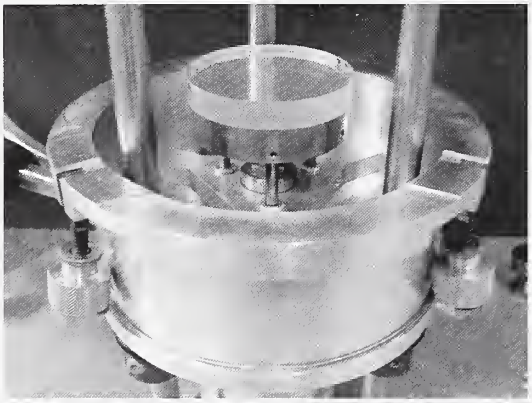
MILESTONE: Finish NIST Technical Note on LTCC measurement methods and attend LTCC and IPC workshops and standards committees.

We are developing improved and new techniques for characterizing bulk and thin-film ferroelectrics.

MILESTONE: By 2001, develop software for a dielectric resonator technique for measuring ferroelectric thin materials and films.

In order to support the needs of the Justice Department we are developing liquid characterization techniques and developing phantom materials that emulate the body's electrical properties.

MILESTONE: In 2001, develop and measure carbon-black silicone composites and liquids to be used as biological phantom materials.



Cylindrical Cavity Resonator for Dielectric Standard Reference Material (SRM) Characterizion.

To further basic research in dielectrics, we are developing new relaxation models for dielectric and magnetic response.

MILESTONE: By 2001, write paper on magnetic relaxation using statistical-mechanical models that summarizes the response of simultaneously applied electric and magnetic fields.

We are developing standard reference materials (SRM), including Rexolite and fused silica.

MILESTONE: By 2001, finish SRM development.

Accomplishments

- Complete software for Split-Cylinder Resonator Model, currently used in industry. Completed and compared mode-matching and least-squares boundary residual models for measuring the permittivity of dielectric materials using the split-cylinder resonator method. These new theoretical models were incorporated into automated measurement software that allow for quick, nondestructive and accurate permittivity measurements of planar dielectric materials such as ceramic substrates and printed-wiring boards.

- Organized, along with MSEL's Ceramics Division, a series of meetings between NIST researchers and manufacturers of LTCC (low-temperature co-fired ceramic) materials and products. At meetings in Gaithersburg (November), Boulder (April) and Los Angeles (August), NIST personnel from both EEEL and MSEL gave presentations on measurements methods and modeling techniques relevant to LTTC materials. In addition, members of the LTCC industry outlined their measurement and modeling needs and proposed that NIST organize a consortium to address these needs.

- Collaborated with Ceramics Division of MSEL to study the effects of cation ordering on permittivity, dielectric loss, and temperature coefficient with respect to frequency on complex perovskites. Complex perovskites with two or more cations located on the octahedrally coordinated B-sites are attractive candidates for use as dielectric resonators and filters in wireless communication systems. We pursued collaborative work with MSEL Ceramics Division (I. Levin, J. Chan, J. Maslar, and T. Vanderah) on the correlation of microwave dielectric properties with the chemical structure of various polymorphs of $Ca_4Nb_2O_9$. The study demonstrated systematic dependence of both permittivity and temperature coefficient on the ordering of Ca and Nb on B-sites of perovskite structure. Decreases in real permittivity and changes of temperature coefficient were seen to correlate with compressed (strengthened) bonds between higher-valent Nb cations on B-sites.

- Developed synthetic materials that emulate the conductivity of human body tissues. In the last year we have been developing materials that emulate the conductivity of human tissue. The work is funded by the Justice Department for use in modeling metal detectors performance. The Justice Department wishes to have well-characterized phantom materials over a frequency range of 100 Hz to 10 MHz to be used to test the sensitivity of metal detectors. The Electromagnetic Properties of Materials Project has studied past research on phantom materials and is in the process of testing both liquid and solid materials. Two approaches are being studied, the first is a liquid material with a mixture of salts and low-conductivity liquids. The second approach uses a solid based on carbon black in silicone. Measurements are being made on a LCR meter using a shielded open-circuited holder. A mode-match model has been developed for the sample holder. Data for human tissues have been gleaned from the literature.

FY Deliverables

Recent Publications

BAKER-JARVIS, J. R.; A Generalized Dielectric Polarization Evolution Equation; IEEE Trans. Dielectr. Electr. Insul., Vol. 7, No. 3, pp. 374-386; June 2000

JONES, C. A.; GROSVENOR, J. H.; WEIL, C. M.; RF Material Characterization Using a Large-Diameter (76.8 mm) Coaxial Air Line; Proc., Intl. Microwave Conf. MIKON, 22-24 May 2000, Warsaw, Poland, Vol. 1, pp. 417-420; May 2000

KRUPKA, J.; BAKER-JARVIS, J. R GEYER, R. G.; Measurements of the Complex Permittivity of Single-Crystal and Ceramic Strontium Titanate at Microwave Frequencies and Cryogenic Temperatures; Proc., Intl. Microwave Conf. MIKON, 15 May 2000, Warsaw, Poland, Vol. 1, pp. 301-304; May 2000

BAKER-JARVIS, J. R.; RIDDLE, B. F.; Dielectric Measurements of Substrates and Packaging Materials; Proc., Intl. Conf. on High Density Interconnect and System Packaging, 26-28 April 2000, Denver, CO, pp. 177-181; April 2000

SYNOWCZYNSKI, J.; DEWING, G.; GEYER, R. G.; Acceptor Doping of Barium Strontium Titanate and Magnesium Oxide Composites; Proc., Am. Ceram. Soc., 25-28 April 2000, Indianapolis, IN, pp. 241-259; April 2000

JONES, C. A.; GROSVENOR, J. H.; WEIL, C. M.; RF Material Characterization Using a Large-Diameter (76.8 mm) Coaxial Air Line; NIST TN 1517; February 2000

GEYER, R. G.; Complex Permittivity and Permeability of Ferrite Ceramics at Microwave Frequencies; Trans. Am. Ceram. Soc., Vol. 100, pp. 195-215; 1999

GEYER, R. G.; KABOS, P.; Magnetic Switching; Wiley Encyclopedia of Electrical and Electronics Engineering, Vol. 12, pp. 179-191; 1999

HOLLOWAY, C. L.; BAKER-JARVIS, J. R.; JOHNK, R. T.; GEYER, R. G.; Electromagnetic Ferrite Tile Absorber; Wiley Encyclopedia of Electrical and Electronics Engineering, Vol. 6, pp. 429-440; 1999

KRUPKA, J.; DERZAKOWSKI, K.; TOBAR, M.; HARTNETT, J. G.; GEYER, R. G.; Complex Permittivity of Some Ultra-Low Loss Crystals at Cryogenic Temperature; Meas. Sci. Tech. J., Vol. 10, pp. 387-392; October 1999

HARNETT, J. G.; TOBAR, M. E.; MANN, A. G.; INVANOV, E. N.; KRUPKA, J.; GEYER, R. G.; Frequency-Temperature Compensation in Ti3+ and Ti4+ Doped Sapphire Whispering Gallery Mode Resonators; IEEE Trans. Ultrasonics, Ferroelectrics, and Frequency Control, Vol. 46, No. 4, pp. 993-999; July 1999

BAKER-JARVIS, J. R.; RIDDLE, B. F.; YOUNG, A.; Ion Dynamics Near Charged Electrodes with Excluded Volume Effect; IEEE Trans. Dielectr. Electr. Insulation, Vol. 6, No. 2, pp. 226-235; April 1999

BAKER-JARVIS, J. R.; RIDDLE, B. F.; JANEZIC, M. D.; Dielectric and Magnetic Properties of Printed Wiring Boards and Other Substrate Materials; NIST TN 1512; March 1999

JANEZIC, M. D.; JARGON, J. A.; Complex Permittivity from Propagation Constant Measurements; IEEE Microwave Guided Wave Lett., Vol. 9, No. 2, pp. 76-78; February 1999

BAKER-JARVIS, J. R.; JONES, C. A.; RIDDLE, B. F.; Electrical Properties and Dielectric Relaxation of DNA in Solution; NIST TN 1509; November 1998

WEIL, C. M.; JANEZIC, M. D.; JONES, C. A.; VANZURA, E. J.; Measurement Intercomparisons of Dielectric and Magnetic Material Characterization; Proc., Conf. on Prec. Electromagn. Meas., 6-10 July 1998, Washington, DC, pp. 481-482; July 1998

GEYER, R. G.; JONES, C. A.; KRUPKA, J.; Microwave Characterization of Dielectric Ceramics for Wireless Communiucations; Advances in Dielectric Ceramic Materials, Vol. 88, pp. 75-91; May 1998

GEYER, R. G.; JONES, C. A.; KRUPKA, J.; Complex Permeability Measurements of Ferrite Ceramics Used in Wireless Communications; Advances in Dielectric Ceramic Materials, Vol. 88, pp. 93-113; May 1998

GEYER, R. C.; BAKER-JARVIS, J. R.; VANDERAH, T. A.; MANTESE, J. F; Complex Permittivity and Permeability Estimation of Composite Electroceramics; Advances in Dielectric Ceramic Materials, Vol. 88, pp. 115-129; May 1998

KRUPKA, J.; WEIL, C. M.; Recent Advances in Metrology for the Electromagnetic Characterization of Bulk Materials at Microwave Frequencies; Proc., MIXON XII, Intl. Microwave Conf., 20-22 May 1998, Krakow, Poland, pp. 243-253; May 1998

BAKER-JARVIS, J. R.; JONES, C. A.; JANEZIC, M. D.; Shielded Open-Circuited Sample Holder for Dielectric Measurements of Solids and Liquids; IEEE Trans. Instrum. Meas., Vol. 47, No. 2, pp. 338-344; April 1998

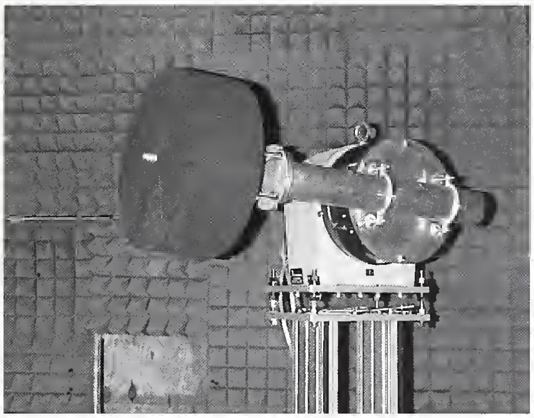
JANEZIC, M. D.; BAKER-JARVIS, J. R.; Full-Wave Analysis of a Split-Cylinder Resonator for Nondesructive Permittivity Measurements; IEEE Trans. Microwave Theory Tech., Vol. 47, No. 10, pp. 2014-2020; October 1999

Antenna and Antenna Systems

Antenna Measurement Theory and Application Systems

Project Goals

To develop, refine, and extend measurement techniques to meet current requirements and to anticipate future needs for accurate antenna characterization.



Setup for a quiet-zone scan. In an actual measurement the exposed metal on the rotator and tower would be covered with microwave absorber. The probe is just visible in the left center, slightly beyond the end of the absorber.

Customer Needs

Microwave antenna hardware continues to become more sophisticated over the years and NIST is tasked with providing correspondingly sophisticated measurement support. Current demands include:

Improved accuracy: High-performance systems, especially those that are satellite-based, require maintenance of tighter tolerances.

Higher frequencies: Millimeter-wave applications up to 500 GHz have been proposed. NIST routinely receives requests for measurements above 75 GHz (near the current limit of support.)

Low-sidelobe antennas: Military and commercial communications applications increasingly require sidelobe levels of 50 dB below peak, or better, a range where measurement by standard techniques is difficult.

Complex phased-array antennas: Large, often electronically steerable phased arrays require special diagnostic tests to ensure full functionality.

In situ and remote measurements: Many systems cannot be transported simply to a measurement laboratory. Robust techniques are needed for on-site testing.

Production line evaluation: Techniques are required that emphasize speed and economy, possibly at the expense of the ultimate in accuracy.

Evaluation of anechoic chambers and compact ranges: A number of widely used measurement systems rely on establishing a well characterized test field. Near-field methods can be used to evaluate and analyze the quality of these test fields.

Technical Strategy

NIST must expand the covered frequency range for antenna calibrations to meet the demands of government and industry.

MILESTONE: By 2001, upgrade services to include the band 75 to 110 GHz. By 2002, upgrade services to include the band 110 to 170 GHz and develop metrology for the band 170 to 260 GHz.

To ensure accuracy, it is necessary to determine the quality of the incident field in the quiet zone of compact or far-field ranges.

MILESTONE: By 2001, Perform sample measurements of a known target to introduce sources of non-ideal fields and verify that they can be detected.

Measurements, especially at millimeter-wave frequencies, often require probe-positioning tolerances that are difficult to maintain. The position of the probe can be accurately tracked with a laser interferometer. This tracking information can be used efficiently to correct measurement results for probe-position errors.

MILESTONE: By 2001, adapt probe position-correction software (that has been completed for planar near-field scanning) for application to spherical and cylindrical near-field scanning.

One of the larger sources of error in near-field measurements is multiple interactions between the probe and test antenna. Although this effect is

Technical Contact:
Andrew G. Repjar

Staff-Years:
3.0 professionals
1.0 technician

Funding Sources:
NIST (70%)
Other (30%)

Parent Program:
Radio-frequency

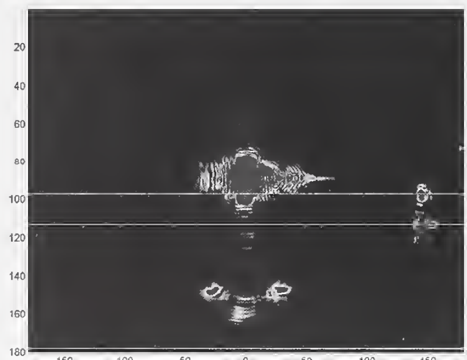
included in the general theory, there is currently no practical compensation method.

MILESTONE: By 2001, complete a study on compensation for multiple-interaction errors, possibly involving a simplified scattering model for electrically small probes.

In planar near-field scanning, measurements are theoretically required over an infinite plane. In practice, the necessity of truncation leads to pattern-prediction errors that can be especially serious for broad-beam antennas. There are several promising methods for reducing truncation errors.

MILESTONE: By 2002, complete a study on the reduction of truncation errors using maximum-entropy methods and/or representations by prolate spheroidal functions.

The near-field extrapolation method, developed at NIST, is one of the more accurate ways of characterizing the on-axis gain and polarization properties of antennas. Further improvement is still possible, however.



Unfocussed image of measurement laboratory at 16 GHz, showing illuminating source horn (center) and ladder (right). At the bottom can be seen the mounting table with rails.

MILESTONE: By 2002, extend the extrapolation software to take full advantage of phase information and to analyze the conditioning of the algorithm.

Large, high-performance antennas, especially those deployed in space, require calibration to ensure optimum performance.

MILESTONE: By 2002, develop a method for remotely calibrating large antennas.

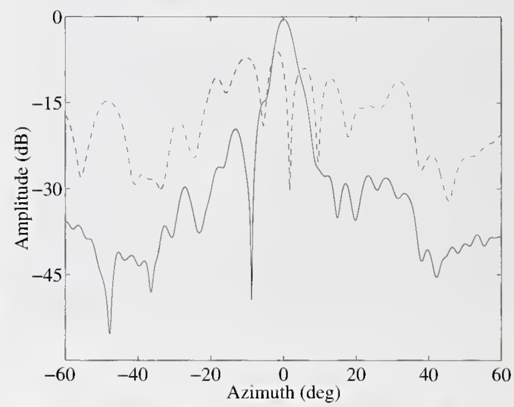
Accomplishments

- Preliminary quiet-zone measurement data have been acquired. Initial results are promising since it is possible to see the effects of an unwanted scattering source (a ladder) intentionally placed in the range.

- A 3D probe position-error correction scheme has been developed and published for planar near-field scanning applications. Software is available to the public.

- Quiet-zone evaluation software is complete. This software has been used to image the effects of a ladder placed in the range.

- Acquired millimeter-wave receiver and signal sources for antenna measurements in the 75 to 110 GHz Frequency range.



Antenna pattern (solid line) and the result of a simulated measurement (dashed line) where random probe position errors on the order of a wavelength have been introduced (normal measurement spacing is ½ wavelength). NIST software permits accurate, efficient recovery of the original pattern. The corrected result is not distinguishable from the original on the scale of this plot.

FY Deliverables

External Recognition

Christopher Holloway spent three months as an invited Visiting Professor at the University of Rome Italy, where he collaborated with their EMC Group in conducting research and giving lectures.

Short Courses

NIST offers annually, with the Georgia Institute of Technology, an introductory course on antenna measurements. Every other year NIST presents an in-depth technical course restricted to near-field methods, pioneered at NIST.

Software

Currently available for planar, cylindrical, and spherical scanning applications. Probe position-correction software is available for the planar methods. Quiet-zone evaluation and imaging programs are expected by 2001.

Recent Publications

Gorier, J. R.; Canales, S.; "Alignment procedure for field evaluation measurements on a spherical surface," Proc. Antenna Meas. Tech. Assoc., pp. 2–7, Oct. 1999

Newell, A. C.; "Error analysis techniques for planar near-field measurements," IEEE Trans. Antennas Propagat., vol. AP-36, pp. 754–768, May 1998

Wittmann, R. C.; Alpert, B. K.; Francis, M.H.; "Near-field antenna measurements using nonideal measurement locations," IEEE Trans. Antennas Propagat., vol. AP-46, pp. 716–722, May 1998

Stubenrauch, C. F.; MacReynolds, K.; Norgard, J. D.; Seifert, M.; Cormack, R. H.; "Microwave far-field patterns determined from infrared holograms," Proc. Antenna Meas. Tech. Assoc., pp. 125–130, Nov. 1997

Wittmann, R. C.; Black, D. N.; "Quiet-zone evaluation using a spherical synthetic aperture radar," Proc. Antenna Meas. Tech. Assoc., pp. 406–410, Sept. 1996

Antenna and Antenna Systems

Metrology for Antenna, Wireless, and Space Systems

Technical Contact:
Michael H. Francis

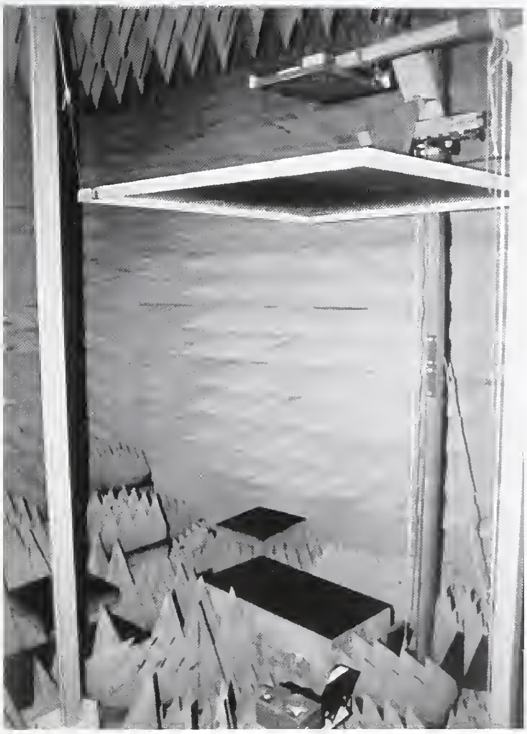
Staff-Years:
3.0 professionals
1.0 technician

Funding Sources:
NIST (70%)Other (30%

Parent Program:
Radio-frequency

Project Goals

To maintain and develop the standards, methods, and instrumentation for measuring critical performance parameters of earth terminal, satellite, and other critical antenna systems, such as those associated with public safety.



Set-up for thermal imaging holography measurements. The large rectangular object is the resistive screen; the test antenna is in the upper center, the reference horn in the upper right, and the infrared camera is in the lower center of the picture

Customer Needs

Satellite communication is a finely tuned technology requiring accurate measurements of antenna gain, noise temperature, G/T (system gain divided by system temperature), and EIRP (effective isotropic radiated power) to ensure optimum performance. Ground stations and test ranges that monitor the performance of commercial and government satellites require traceability to NIST standards. Measured satellite performance is used to determine incentive-clause payments to satellite contractors or charges billed to users or lessees that the results produced at these facilities must be of the highest accuracy. New capabilities are needed to support anticipated technologies, such as anticollision radars. NIST traceability is also required by law enforcement agencies to ensure the accuracy of their speed measurement devices — down-the-road radar, across-the-road radar, and lidar.

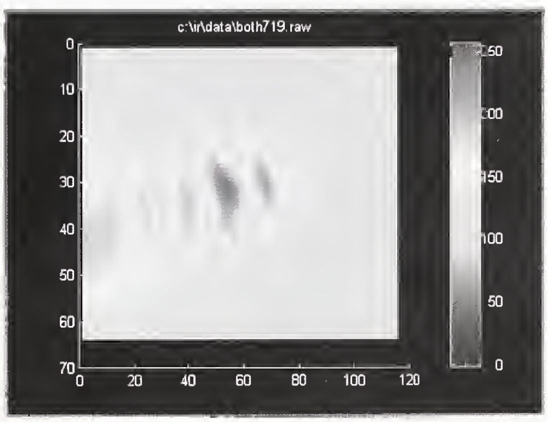
Technical Strategy

NIST currently maintains measurement standards and capabilities for frequencies from 1.5 to 75 GHz. Some automobile anticollision radars will operate at frequencies from 76 to 77 GHz and aircraft anticollision radars will operate at frequencies from 94 to 96 GHz.

MILESTONE: By 2001, define anticollision radar system testing requirements and evaluate existing metrology for system parameter measurements.

MILESTONE: By 2002, develop metrology and artifact standards for automobile anticollision radars.

MILESTONE: By 2003, develop metrology and artifact standards for aircraft anticollision radars.



Thermal image of the near-field interference pattern of a microstrip antenna and standard gain horn.

Antenna systems are often tested in indoor laboratory environments. The outdoor environment in which they operate has additional sources of noise and may add to the system noise temperature. To accurately predict the performance of antenna systems in the operating environment from their performance in the laboratory, it is necessary to be able to predict the noise due to sources in the operating environment.

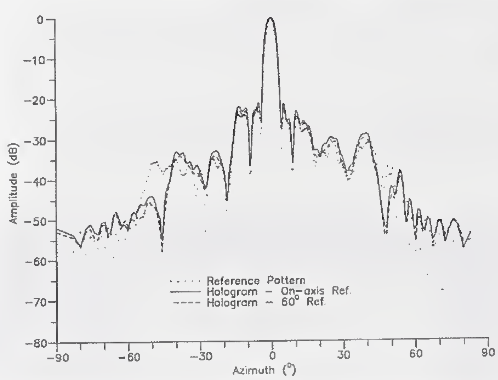
MILESTONE: By 2002, determine the G/T of an antenna both indoors and outdoors and evaluate the ability to predict outdoor performance from indoor measurement.

Large antenna systems cannot be evaluated in an indoor laboratory environment. A method is needed to evaluate large antenna systems in situ.

MILESTONE: By 2001, develop thermal holographic methods for diagnostics of large antenna systems.

To ensure the accuracy of police speed measuring devices, the International Association of Chiefs of Police (IACP) must have adequate test equipment.

MILESTONE: By 2001, provide a working lidar speed-simulator system to be used at an IACP laboratory to be established at the University of North Florida. By 2001, develop and provide prototype across-the-road radar speed simulators.



Comparison of the far field as determined by conventional near-field methods (dotted line) and from thermal imaged holograms (dashed and solid lines).

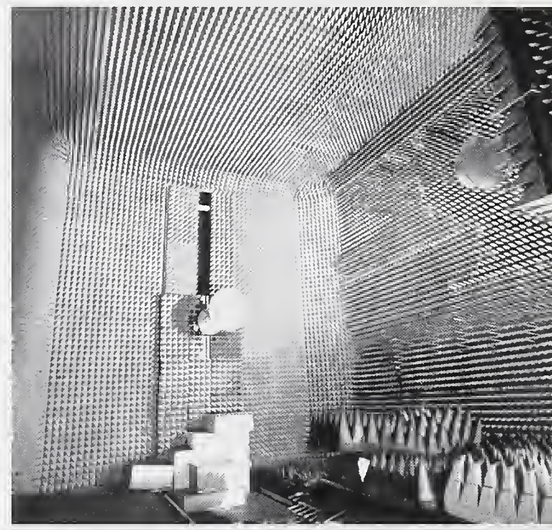
Accomplishments

- Developed the theory of using infrared/microwave holography for transmitting antenna measurements in collaboration with the University of Colorado, Colorado Springs (UCCS). As part of this effort, NIST performed tests and analyses on a small 4 x 4-element array and a 1.2-m dish operating at 4 GHz.

- Established program to provide support for the International Association of Chiefs of Police (IACP) testing program for traffic speed-measurement devices including down-the-road radar, across-the-road radar, and lidar.

- Completed and tested a prototype across-the-road radar speed simulator for use in IACP test laboratories.

- Evaluated software developed under a Small Business Innovative Research grant that predicts outdoor antenna system performance from indoor measurements.



The NIST probe pattern range with the fixed probe located near the center of the photo and the moving probe located on the moving tower in the upper right of the photo.

FY Deliverables

Calibrations

Completed measurements for Space Systems Loral on two standard gain horns, two dual-port linearly polarized probes, and two dual-port circularly polarized probes. These measurements were done in the WR-137 (5.85 – 8.2 GHz) frequency band. These probes will be used as near-field reference probes for measuring communications satellite antennas.

Completed measurements for EMS Technologies on two WR-650 (1.12 – 1.7 GHz) pyramidal horns for on-axis gain at six frequencies, plus stepped gain.

Completed measurements for TRW Space and Electronics for on-axis gain at eight frequencies on a WR-28 (26.5 – 40 GHz) horn lens antenna.

Completed measurements for Nearfield Systems Inc. on a WR-42 (18 – 26.5 GHz) Memco dual-port circularly polarized probe at five frequencies for on-axis gain, polarization, and patterns.

Completed measurements for Nearfield Systems Inc. WR-28 (26.5 to 40 GHz) Memco dual-port circularly polarized probe at five frequencies for on axis-gain, polarization, and patterns. Performed 276 tests on 212 items for 72 companies and government agencies that generated $264,742 income (October 1, 1998 to August 27, 1999).

External Recognition

NIST, AMTA, along with Ball Aerospace, will host the 2001 AMTA Symposium in Denver, CO October 21-16, 2001.

Mike Francis was elected President of the Antenna Measurement Techniques Association (AMTA) for the year 2000. AMTA is an international organization with a membership of about 400 scientists and engineers.

Software

Planar Near-Field Library

Cylindrical Near-Field Library

Spherical Near-Field Library

Atmospheric Attenuation Library

Recent Publications

MacReynolds, K and Francis, M.H., "Antenna Gain Measurements: The Three-Antenna Extrapolation Method," Proceedings of the Antenna Measurement Techniques Association, pp. 370-375, October 1999

Ondrejka, A.R. and Johnk, R.T., "Portable Calibrator for Across-the-Road Radar Systems," NIST Tech. Note 1398, May 1998

Antenna and Antenna Systems

Metrology for Radar Cross Section Systems

Project Goals

To assist the Department of Defense (DOD) and industrial radar cross section (RCS) measurement ranges to create and implement a National DOD Quality Assurance Program to ensure high quality RCS calibrations and measurements with stated uncertainties.

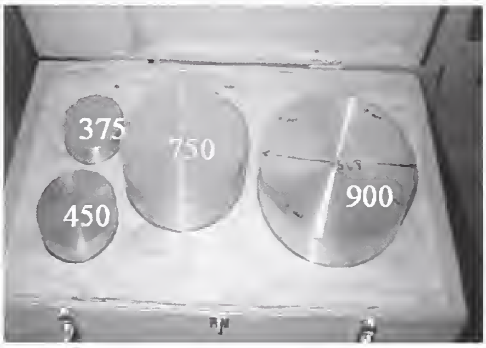
Customer Needs

RCS measurements on complex targets, such as aircraft, ships, or missiles, are made at different types of RCS measurement ranges such as, a compact range (indoor static), an outdoor static or an outdoor dynamic facility. Industry-wide measurements taken at various ranges on the same targets must agree with each other within stated uncertainties to increase confidence in RCS measurements. Although the sources of uncertainty are well known, a comprehensive determination of the magnitudes of uncertainties in RCS calibrations and measurements has yet to be accomplished at any of the government or industrial ranges. Such studies are essential at every RCS measurement range, if the US RCS industry is to maintain its world leadership well into the new century. To satisfy this requirement we need to establish well-formulated procedures that measurement ranges can use to determine their uncertainties.

Technical Strategy

The complex measurement systems and practices at RCS ranges should be documented uniformly throughout industry to allow for meaningful comparison of capabilities and important range-to-range differences. The framework of a RCS Range Book, in the context of a DOD RCS Self-Certification Program, has been proposed to ensure community-wide compliance. A DOD Demonstration Project is in progress to assess the feasibility and usefulness of such a program.

A thorough technical analysis of the currently followed measurement procedures is essential to reveal areas of strength and weaknesses and to foster appropriate improvements.



The basic cylinder set used to calibrate static RCS measurement systems in the frequency range of 2-18 GHz. The cylinders are made of aluminum, and are manufactured to a tolerance of ±0.0127 cm.

Currently, the following areas of research in RCS measurement technology require attention:

(1) The set of calibration artifacts used by industry should be enhanced to assess and improve calibration accuracy.

(2) Defendable range-specific uncertainty analyses are needed throughout the RCS industry.

(3) A RCS interlaboratory comparison program and the corresponding technology has to be developed to enhance confidence in our uncertainty analysis, in the calibration of RCS artifacts and in the measurements on unknown targets.

MILESTONE: By 2001, continue the RCS Range Book reviews as required by industry. Work closely with selected RCS ranges to develop detailed procedures to determine RCS calibration and measurement uncertainty. Develop and publish an uncertainty analysis both for monostatic and bistatic RCS measurements at selected facilities. Develop an expanded set of RCS calibration artifacts to be able to calibrate the system at various signal levels of interest, and conduct an interlaboratory comparison study to assess the results. Develop RCS calibration procedures in the Ultra-Wide-Band Time-domain Reflectivity Laboratory here at NIST, and demonstrate fully the uncertainty analysis procedures needed to assign uncertainties to RCS measurements.

MILESTONE: By 2002, conclude the RCS Range Book reviews for industry, and publish a report summarizing NIST's observations as to the usefulness and feasibility of the DOD self-certification process; make appropriate

Technical Contact:
Lorant Muth

Staff-Years:
2.0 professionals

Funding Sources:
NIST (20%)
Other (10%)

Parent Program:
Radio-frequency

recommendations for improvements. Continue the research and development as defined in FY 2001. Make recommendations for further improvements to RCS calibration measurement procedures.

MILESTONE: By 2001, conduct RCS Range Book reviews for the DOD Demonstration Project in support of the National DOD RCS Range Certification Program. Provide in-depth comments to improve on the procedures used at the RCS measurement ranges. Fully assess the technical merit and deficiencies of existing calibration and measurement procedures, data-analysis techniques and uncertainty analysis. Publish recommendations for improvements in measurement procedures. Further explore known problems in areas of dynamic sphere calibration, polarimetric calibration, etc. Organize the Fifth RCS Certification Meeting at NIST, Boulder to provide a forum for the RCS community to discuss procedural and technical issues.

Accomplishments

- We reviewed six major government RCS measurement ranges during the first two years of the project. Personnel from each range gave presentations at NIST, Boulder to the RF Fields group over a period of three days to examine the ranges' calibration and measurement procedures, instrumentation, documentation and uncertainty analysis procedures. NIST and the personnel of each RCS measurement range jointly performed preliminary uncertainty analyses.

- We published a general framework for RCS uncertainty analysis (NISTIR 5019) to stimulate interest in RCS uncertainty analysis at RCS measurement ranges. The work was disseminated to the RCS community at conferences and via direct communication. We have collaborated with personnel of the Naval Air Warfare Center, Aircraft Division, Patuxent River, MD to examine in-depth the uncertainties in dynamic sphere calibrations. As a result the uncertainties on dynamic ranges are much better understood, but more work is needed for a complete analysis. The results of this study were published in a NISTIR (see Publications).

- We collaborated with personnel of the Naval Command, Control and Ocean Surveillance Center, San Diego, CA to examine in-depth the uncertainties in dynamic naval ship measurements. The preliminary uncertainty analysis for this range has been published in a NISTIR (see Publications). Several improvements in the calibration procedures have been recommended and adopted as a result of this study.

- We noted several areas for improvement in the dynamic sphere calibration procedures for outdoor ranges. The calibration data exhibited unexplained large variations and contained frequency components that indicated significant electromagnetic interference from unknown sources. Minor modifications to the instrumentation removed the unwanted frequencies. However, large variations in the amplitude of calibration data remained, which indicate possible pointing problems in the radar tracking system. This research is still ongoing today.

- The RCS ranges reported less than satisfactory results with existing polarimetric calibration procedures. We developed a more robust calibration procedure wherein full polarimetric data are obtained using a dihedral rotating around the line-of-sight to the radar. The new procedure allows one to improve the signal-to-noise ratio, and check for alignment problems by exploiting the symmetry properties of the dihedral. Diffraction effects can also be minimized by properly shaping the edges and sides of the dihedral. Presence of unwanted spatial harmonics can indicate problems with the radar. A full uncertainty analysis still needs to be developed for this procedure. We are working with several of the RCS ranges to further study this technique.

- The RCS community has adopted a basic cylinder calibration set (see figure) to test the calibration integrity of monostatic RCS systems. Computed radar cross sections for the cylinder were obtained. These four cylinders were then measured at a number of government and industrial measurement ranges. We have consistently found that measurements agreed with the theoretical RCS within 0.5 dB and we showed that such comparisons demonstrate good repeatability. However, we need more robust independent measurement procedures to determine the measurement uncertainties.

- The DOD Demonstration Project has been established to explore the feasibility and cost of a National DOD RCS Self-Certification Program. Three DOD measurement facilities have undertaken to develop their RCS Range Books, which contain the full documentation of range procedures, as outlined in the ANSI Z-540 standards document. These Range Books have been submitted to a RCS Certification Review Committee for examination and comments. Three Review Committees have been established, and

"It is widely recognized that our national measurement capability needs to be strengthened and improved. I wholly support the goals of the RCS Range Certification Project that will establish sustainable and reasonable quality standards and practices for all ranges supporting our nation's investments in low observable technology. It pleases me greatly to see our organizations cooperating so well on these important topics..."

Richard Paul
Major General, USAF
Commander, AFRI, WPAFB

the AFRL, Patuxent River and NRTF Range Books have been submitted for review. We expect that all three Range Books will be reviewed by early 2001.

- We have organized an annual RCS Certification Meeting for the last four years. The purpose of these meetings is to discuss procedural and technical criteria for a national DOD RCS self-certification program, to discuss known technical issues in RCS calibration and measurements, and to discuss progress on the DOD Demonstration Project. On average, 60 representatives of government and industrial ranges have attended these meetings. In 1999 and 2000, six foreign nationals from the UK and Canada also attended. Feedback has been consistently positive.

- The RCS community has adapted the ANSI Z540 standards document for use by RCS ranges. A Handbook for the Assurance of Radar Cross Section Measurements has been written to assist the RCS community developing their Range Books.

FY Deliverables

Collaborations

RCS uncertainty analysis: Pax River and NRaD Naval facilities, and the RCS community.

Range Books reviews: Pax River, Air Force Research Laboratory, WPAFB, and NRTF.

Polarimetric research: Eglin AFB.

RCS uncertainty workshop: The ElectroScience Laboratory, The Ohio State University, Columbus, OH.

Certification meetings: RCS community.

RCS Range characterization: China Lake, CA.

Standards Committee Participation

IEEE RCS Standards Committee is writing a standards document on RCS calibrations, measurements and imaging. NIST is a major contributor to the document.

Recent Publications

L. A. Muth, "An assessment of the NIST RCS project," Proc. Antenna Meas. Tech. Assoc., Philadelphia, PA, p. 375, 16 - 20 Oct. 2000

L. A. Muth, "Uncertainties in dynamic sphere radar cross section data," Proc. Antenna Meas. Tech. Assoc., Philadelphia, PA, pp. 382 - 386, 16 - 20 Oct. 2000

L. A. Muth, "Radar cross section calibration errors and uncertainties," Proc. Antenna Meas. Tech. Assoc., Monterey Bay, CA, pp. 115 - 119, 4 - 8 Oct. 1999

L. A. Muth, R. Johnk, and D. Novotny, "Errors and uncertainties in Radar Cross Section Measurements," Proc. Nat. Conf. Stand. Lab., Charlotte, NC, pp. 276 - 280, July, 1999

J. P. Skinner, B. M. Kent, R. C. Wittmann, D. L. Mensa, and D. J. Andersh, "Normalization and interpretation of radar images," IEEE Trans. Antennas Propagat., Apr. 1998

J. Sorgnit, P. Mora, L. A. Muth, and R. C. Wittmann, "Uncertainty analysis procedures for dynamic radar cross section measurements at the Atlantic Test Range," National Institute of Standards and Technology NISTIR 5073, Feb. 1998

L. A. Muth, R. C. Wittmann, and B. M. Kent, "Interlaboratory comparisons in radar cross section measurements," Proc. Antenna Meas. Tech. Assoc., Boston, MA, pp. 297 - 302, 17-21 Nov. 1997

B. M. Kent, and L. A. Muth, "Establishing a common RCS range documentation standard based on ANSI/NCSL Z-540-1994-1 and ISO Guide 25," Proc. Antenna Meas. Tech. Assoc., Boston, MA, pp. 291 - 296, 17 - 21 Nov. 1997

L. A. Muth, R. C. Wittmann, and B. M. Kent, "Measurement assurance and certification of radar cross section measurements," Proc. Natl. Conf. Stand. Labs., Atlanta, GA, pp. 555 - 566, 27 - 31 July 1997

L. A. Muth, and R. C. Wittmann, "Calibration of polarimetric radar systems," Proc. IEEE Intl. Symp. Antennas Propagat. Soc., Montreal, Canada, pp. 830 - 833, 14 - 18 July 1997

M. J. Prickett, R. A. Bloomfield, G. A. Kinzel, R. C. Wittmann, and L. A. Muth, "Uncertainty analysis for NRaD radar cross section easurements," National Institute of Standards and Technology, NISTIR 5061, April 1997

Electromagnetic Compatibility

Standard Electromagnetic Fields

Project Goals

To develop methods and techniques for establishing continuous wave electromagnetic (EM) reference fields to 100 GHz. To maintain this measurement capability in support of U.S. industry through traceability and international compatibility of antenna standards.

Customer Needs

Well-defined EM reference fields are necessary for antenna calibrations, antenna research and development, evaluation of EM field probes, and EM interference measurements. Standards requirements need references to establish traceability and international compatibility. Industry requires a NIST-traceable EM field measurement capability to reduce barriers to world-wide acceptance of U.S. products and practices, based on the principles of "one product, one technically valid international standard, one conformity assessment" (1998 MSL Strategic Plan).

Technical Strategy

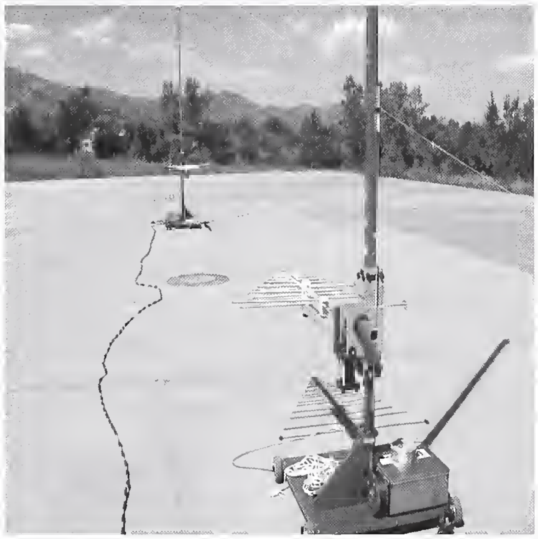
As instrumentation and electronics in general achieve higher clock speeds, measurements are needed at higher frequencies. Techniques based on the lower frequencies can be used to create standard EM fields at these higher frequencies, given facilities and instrumentation. NIST must extend current facilities for these measurements.

MILESTONE: By 2000, extend sensor and antenna calibration capabilities to frequencies above 50 GHz.

OATS (open area test site) facilities are accepted as standard sites for EMC emissions measurements. However, increased ambient signal levels are causing complications in repeatability and accuracy of measurements. New techniques or facilities are needed to help industry combat these problems.

MILESTONE: By 2002, develop robust methods for OATS calibrations in high ambient field environment.

Comparison of EMC emissions measurements at various industrial sites shows large variations. Development of a service to quantify the output from various reference emitters will address variations within U.S. industrial sites. Leadership and guidance from NIST is sought from industry.



Antenna under test at NIST OATS facility

MILESTONE: By 2001, develop RF emissions measurement service for 30 to 1000 MHz. This includes design and evaluation of measurement methodology including uncertainty analysis.

Anechoic chamber facilities are accepted as standard sites for free-space measurements. Different methods, different equipment, and even different corporate philosophy cause variants in measurement results and uncertainties. NIST will provide a focus to these deviations to improve congruity within the U.S. industrial community and elsewhere.

MILESTONE: By 2001, develop technique for characterizing anechoic chambers to establish uncertainty bounds for EM field measurements.

Measurement results performed in anechoic chamber, OATS, and semi-anechoic facilities often disagree. NIST will provide a focus to these deviations to improve congruity within the U.S. industrial community and elsewhere.

Technical Contact:
Dennis G. Camell

Staff-Years:
1.5 professionals

Funding Sources:
NIST (20%)
Other (80%)

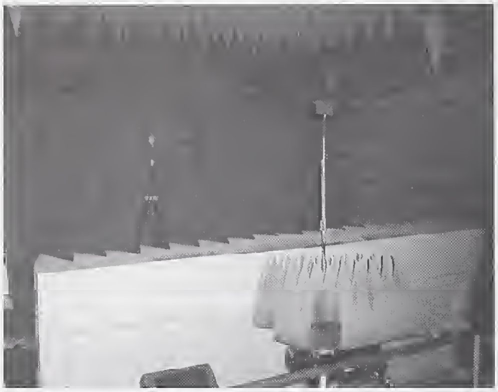
Parent Program:
Electromagnetic Compatibility

"On behalf of the US Council of EMC Laboratories (USCEL), I wish to extend thanks and gratitude for your support of our recently completed EMI Round Robin pilot program. The NIST measurements of the test object ... confirmed the stability of the test object and validated the work of so many participants. The NIST contribution to this program, for the benefit of US EMC laboratories and their clients, is very much appreciated."

Roland Gubisch
Vice-Chair, USCEL

"... consistency is obtained through traceability to NIST ... Liberty Labs has performed intercomparison measurements with the NIST open area test site at Boulder, CO. These antenna calibrations and site intercomparisons allow Liberty Labs to be globally competitive in today's rf emissions testing community..."

Michael Howard
President
Liberty Labs
Kimballton, Iowa



MILESTONE: By 2002, compare results and resolve discrepancies between standard site and standard antenna methods.

Accomplishments

- Testing on the refurbished NIST OATS showed normal site attenuation (NSA) values within ±2.0 dB of predicted values. Improvements on the OATS included a solid steel sheet center, conductive and weatherproof caulking of joints, and serrated edging for better ground contact.

- Method of moments coding resulted in accurate calculations for the effective length and input impedance of the NIST standard dipoles. An error analysis was completed for the uncertainty assessment.

- A detailed analysis of uncertainties for standard-antenna method on OATS was disseminated to industry, other government agencies and standards organizations. Members of the EMC industrial community can apply the methodology to achieve their uncertainty values.

- Comparison between the standard-antenna method and the standard-site method by analysis of uncertainties and measurement repeatability provides test houses with support for current EMC standards.

- Method-of-moments coding resulted in accurate calculations for the effective near-field gain of the NIST standard gain horns in the anechoic chamber. An error analysis was completed for the uncertainty assessment.

FY Deliverables

Calibrations

Five tests were performed on probes/antennas for four companies and/or government agencies covering the frequency range of 10 kHz to 40 GHz using TEM cell, anechoic chamber and OATS test facilities.

Collaborations

As part of the RF emissions calibration development, collaboration was initiated to measure a reference RF emitter through USCEL (the U.S. Council of Electromagnetic Laboratories). This round robin involved 22 EMC test laboratories and provides a reference for cohesion and improved accuracy.

Standards Committees

This year's involvement with ANSI ASC C63 on EMC working group 1-15.6 on 'Geometry Specific Antenna Factors' provided technical insights that led to collaborations with industrial representatives for corrections to current ANSI Standard C63.5 and CISPR 16.

This year's contribution with ANSI ASC C63 on EMC working group 1-13.2 on "Measurement Techniques above 1 GHz" provided technical insights that are leading to collaborations with industrial representatives for corrections to current ANSI Standard C63.4 and CISPR 22.

Direct attendance and participation with ANSI ASC C63 on EMC committees and interaction with its members guide the theoretical and measurement work to future gains.

Recent Publications

Kanda, M., et. al.; - International Comparison GT/RF 86-1 Electric Field Strengths: 27 MHz to 10 GHz; IEEE Trans. Electromag. Compat., vol. 42, no. 2, pp. 190-205; May 2000

Camell, D. G.; Uncertainty Assessment for Standard Antenna Measurements on the Open Area Test Site; NIST TN 1507; Sept. 1998

Cavcey, K. H., Camell, D. G.; Scanning Height for ANSI C63.5 Calibration Methods; Proc., IEEE EMC Symp., 24-28 August 1998, Denver, CO, vol. 2, pp. 935-938

Kwalko, S. F., Kanda, M.; Numerical and Analytical Monopole Nonplanarity Correction Factors; IEEE Trans. Electromag. Compat., vol. 40, no. 2, pp. 176-179, May 1998

Electromagnetic Compatibility

Field Transfer Probe Standards

Project Goals

To provide transfer electromagnetic field probes with calibration traceable to NIST. These probes are used by various US industries including private test laboratories and by other governmental agencies. Due to the wide range of applications, probes with different sensitivities and frequency responses are required. Projections for future spectrum usage indicate that probes with millimeter-wave and terahertz responses need to be developed.

Customer Needs

Many U.S. industries, including the electronics, communications, law enforcement, aircraft, and automotive industries, require accurate quantitative knowledge of the intensity of electromagnetic fields in test chambers, on open area test sites (OATS), or produced by various high power sources. These fields may be generated as standards that are used to calibrate antennas and test hardware for susceptibility to electromagnetic interference, or generated by the electromagnetic emissions from various electronic devices. Although most present applications cover frequencies from about 1 MHz to 10 GHz, systems that operate up to nearly 100 GHz such as for automotive collision avoidance are being developed. Future applications with frequencies above 1 THz are envisioned.

Technical Strategy

NIST maintains parallel efforts both to generate standard reference fields, and to develop the probes required for their accurate measurement. The two efforts complement each other and allow cross checking in order to reduce the uncertainties inherent in each effort. NIST also cooperates with the national test laboratories of our international trading partners to perform round robin testing and intercomparison of various standard antennas and probes. This assures international agreement in their performance and reduces the uncertainties in the areas of metrology that affect international trade. The probes we develop for this purpose also serve as the transfer standards needed by industry and other governmental agencies. Standard probes are designed so that response can be calculated from first principles if possible, and to minimize errors that occur from pickup of unwanted signals. For instance, at frequencies below about 5 GHz, the voltage generated across a tuned half-wave dipole can be calculated quite accurately and monitored via a DC signal on a resistive line. However, this approach is subject to errors introduced by the pickup of ambient electromagnetic fields by the dipole elements. Probes that maintain phase and amplitude information are needed for pulsed signal applications. If electrically coupled to readout instruments, such as probes, they are subject to errors caused by pickup of common-mode signals in the lead wires. In addition to pioneering several probe designs that are currently in use, such as electrically coupled RF dipoles and resistively-tapered dipoles, NIST has applied photonic technologies to electromagnetic field probes. Building on this expertise, we are pursuing programs discussed below.

With commercial applications at millimeter-wave frequencies already under development, the need for standard millimeter-wave probes increases. Our current probes are limited to the low-frequency end of this regime. As frequency increases the losses and uncertainties associated with electrically connected probes become significant. Photonic technologies that transmit the signals along an optical fiber hold a clear advantage. We will explore ways to utilize these advantages to fabricate and test probes with frequency responses above 100 GHz. Techniques that offer possibilities to extend the response to still higher frequencies will be favored. Thermo-optic probes already explored by NIST will be reviewed in this context.

MILESTONE: By 2003, demonstrate a probe with frequency response of 100 GHz that also has the potential to become a transfer standard.

Electromagnetic compatibility testing of large structures, such as aircraft, often requires intense fields that are only available close to high-power, pulsed sources. In these near-field regions, neither the electric nor the magnetic components alone give an accurate measure of the total intensity. NIST has demonstrated a loop antenna with double gaps that simultaneously measures both the electric and magnetic components of the field. When coupled to appropriate

Technical Contact:
Keith D. Masterson

Staff-Years:
1.5 professionals
0.5 technicians

Funding Sources:
NIST (50%)
Other (50%)

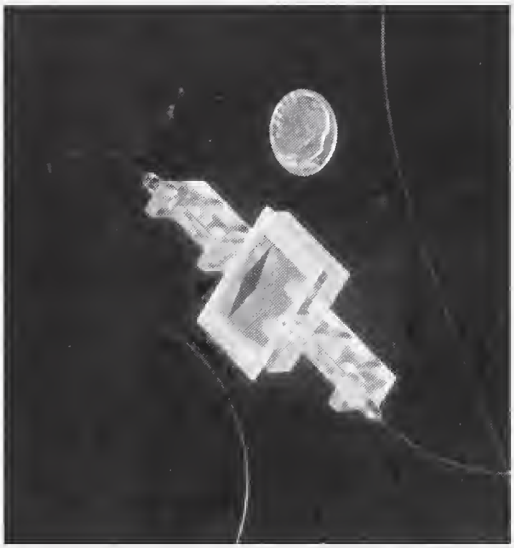
Parent Program:
Electromagnetic Compatibility

instrumentation through optical fibers, it is ideally suited for accurately measuring such fields. NIST is building a field-usable system that will further demonstrate the utility of such measurements and that will be a prototype transfer standard for simultaneous measurement of electric and magnetic fields.

MILESTONE: By 2001, demonstrate and document a transfer standard that can simultaneously measure both the electric and magnetic fields at frequencies up to 500 MHz.

"H-P is currently working to develop a new, commercially-available source based on the NIST spherical radiator. H-P would like to anchor our comparisons to an internationally-recognized site. We support NIST's recent plans to build such a site ..."

Lowell Kolb
Senior Engineer
Hewlett-Packard Co.
Ft. Collins, CO



Integrated resistively-tapered dipole and electromagnetic modulator

Standard RF Dipole

NIST provides calibration services for antennas used commercially in EMC testing. The frequencies of interest are often in the 1 to 400 MHz range, where the electromagnetic wavelength is too long for the tests to be done in existing enclosed test chambers. For these calibrations, we use an open area test site (OATS) that consists of a smooth conducting ground plane about 50 m wide that is situated in an area with a relatively low ambient EM-field background. Unfortunately, the rise in wireless telecommunications, ranging from commercial radio to cellular phones, has lead to an increase in the ambient field levels and a resulting increase in measurement uncertainty when using such outdoor sites. OATS are also used by commercially operated test laboratories and by numerous companies for testing their own products. Thus, they are located in many parts of the country and in many different ambient environments. The strength of the test fields are determined by measurements using standard electrically coupled dipole antennas. NIST has fabricated a Standard RF Dipole system with optical-fiber linkage that reduces errors due to ambient signals and common-mode pickup. Preliminary measurements show that it has a frequency response up to 1.5 GHz. Additional characterization is needed to complete this project.

MILESTONE: By 2002, perform error analysis and complete documentation for the standard RF dipole system. Demonstrate its utility by mapping the field amplitude and phase uniformity over a typical test volume at the NIST outdoor area test site.

Accomplishments

- Developed an RF dipole probe with electrically conducting leads that has been adopted as a standard by national test laboratories in the UK and Austria.
- Developed tuned, half-wave antennas that cover a frequency range from 30 MHz to 1 GHz and have carefully calculated their response.
- Developed resistively tapered dipole probes with frequency responses up to 40 GHz. Probes based on this design are now being produced commercially by private industry.
- Developed a thermo-optic probe with millimeter-wave frequency response.
- Fabricated and tested probes with resistively-tapered dipoles and electro-optic coupling for measuring pulsed electromagnetic fields with bandwidths up to 5 GHz and amplitudes up to 40 kV/m.
- Fabricated a standard RF-dipole with electro-optic coupling that covers a range from 10 MHz to 1.5 GHz.

FY Deliverables

Recent Publications

S.F. Kwalko and M. Kanda, "The Effective Length and Input Impedance of the NIST Standard Dipole," IEEE Trans. Electromagn. Compat., EMC-39(4), pp. 404-408, 1997

Keith D. Masterson, David R. Novotny, and Kenneth H. Cavcey, "Standard Antennas Designed with Electro-Optic Modulators and Optical-Fiber Linkage," in H.E.Brandt (ed.) Intense Microwave Pulses IV, SPIE Proceedings, Vol. 2843, pp.188-196, Bellingham, Washington, 1996

Electromagnetic Compatibility

Time-Domain Free-Field Electromagnetic Metrology

Technical Contact:
Robert T. Johnk

Staff-Years:
2.0 professionals
0.5 technicians

Funding Sources:
NIST (60%)
Other (40%)

Parent Program:
Electromagnetic Compatibility

Project Goals

Develop basic metrology and measurement techniques for a wide variety of applications such as antenna and sensor calibrations, EMC measurement facilities evaluation, shielding performance of commercial aircraft, non-destructive testing of electrical material properties, and precision standard-field generation.

Customer Needs

The burgeoning consumer electronics and wireless revolutions are placing a huge burden on the EMC regulatory communities. With the vast proliferation of electronics systems of all types and sizes, the emissions and immunity performance of these systems is of paramount importance, affecting issues such as health, safety, international trade, and U.S. competitiveness. The march of technology is relentless, and newer, more accurate, and more efficient metrological innovations need to be developed to keep pace with the increasing performance, speed, and frequency. The time-domain free-field project is well placed to provide cutting-edge innovation and support for this revolution.

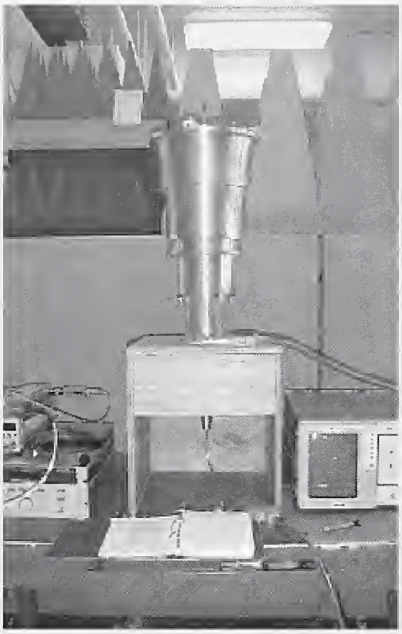
Technical Strategy

The Time-domain Free-Field Electromagnetic Metrology Project's primary focus is to perform ultrawideband electromagnetic measurements using swept frequency or direct pulse systems. Both time-domain and frequency-domain electromagnetic quantities can be extracted from our measurements. These systems exhibit high spatial resolution that can be exploited to perform a wide variety of measurements and extract useful information quickly and accurately. We have developed ultrawideband systems to determine the materials properties of dielectric panels (low-loss and high-loss), evaluate RF absorbers at both normal and oblique incidence angles, characterize electromagnetic (EM) facilities (anechoic and semi-anechoic chambers), shielded rooms, reverberation chambers, and OATS facilities), perform ultrawideband RCS measurements, and evaluate shielding performance of materials and electromagnetic penetration into commercial aircraft. We have performed antenna and sensor calibrations up to 14 GHz on our Cone and Ground plane facility. We are currently designing the Co-Conical Field Generation System, a closed-system test cell capable of testing antennas, sensors, and probes from 10 MHz to 45 GHz. EM modeling and analysis is an integral part of our program. In addition to standard EM theory, many numerical techniques, such as finite difference time-domain (FDTD), finite-element modeling (FEM), and variational methods, are used to predict system performance and improve, as well as validate, our measurements. In addition, we are continually engaged in advancing the characterization of, and reducing the measurement uncertainties of our systems.

Evaluation of a commercial OATS facility using a portable NIST time-domain measurement system.

MILESTONE: By 2003, develop a rapid OATS evaluation measurement system that covers the frequency range from 30 MHz to 6 GHz.

Information technology equipment (ITE) is operating at ever-faster speeds. Fundamental bus data rates are currently faster than 1 GHz. In order to perform meaningful measurements of these devices, a frequency range from 30 MHz to 6 GHz must be covered. Current ANSI and IEC standards provide coverage only up to 1 GHz. There are currently no standards for test procedures and setups above 1 GHz! As operational frequencies increase further, the ability to characterize the measurement facilities becomes more critical. The use of NIST-developed free-field time-domain measurement techniques will play a key role in the development of new facility evaluation techniques and contribute significantly to the development of new international standards above 1 GHz.



Prototype Co-Conical Field Generation System.

MILESTONE: By 2002, develop a low-cost, ultra wideband measurement system for the performance evaluation of EMC measurement facilities.

Faster information technology equipment and wireless advances have vastly increased the frequency range over which emissions and immunity measurements must be performed. This, in turn, has increased the demand for quality measurements facilities. The quality of the facility and achievable measurement uncertainties are of paramount importance if good measurement fidelity is to be realized, particularly at higher frequencies. In order to assess these effects, NIST engineers are developing an ultrawideband time-domain measurement system for the evaluation of EMC absorber-lined chambers. The goal of this effort is to provide coverage and site analysis capability in the frequency band from 30 MHz to 6 GHz. This system will use time-domain transmission measurements to compute the performance of absorber-lined chambers (both full and semi-anechoic). Not only will this system provide fast and accurate chamber performance data, it will completely eliminate the need for a separate antenna calibration thereby cutting cost and improving efficiency.

MILESTONE: By 2001, develop a cone and ground plane sensor and antenna calibration facility that covers the 30 MHz to 18 GHz frequency range.

Absorber-lined chamber testing using NIST-developed time-domain fast-pulse measurement techniques.

D-Dot Sensor calibration using a cone and ground plane standard- field generation system.

Accurate and reliable primary standards will play a key role in the development of next-generation measurement techniques. The central component of this program is a large cone and ground plane system that is currently being constructed at NIST-Boulder. This facility will be capable of generating standard fields from 30 MHz to 18 GHz and accommodate a wide variety of practical measurements covering antenna and sensor calibrations, precision scattering measurements, and EMC shielding performance evaluations. This system will incorporate a moveable cone system that will permit the simulation of some features of OATS

" I would like take this opportunity to make you (Dennis Friday) aware of the outstanding assistance provided by members of your staff to the Hach Company. Robert Johnk's, David Novotny's, and Claude Weil's efforts, guidance, and counsel have proven invaluable in our effort to understand the electromagnetic behavior of our compact anechoic chamber."

Michael Taylor, Principal EMC Compliance Engineer, Engineer
Hach Company

environments for the development and verification of next-generation measurement techniques. New EMC measurement techniques will be essential if NIST is to remain a viable player in the 21st century. This facility will also be a valuable tool for NIST participation in domestic and international EMC standards committees such as ANSI and IEC.

Accomplishments

The NIST free-field time-domain project has made significant advances during the decade of the 90's. Some of the more significant advances are:

- Active participation in domestic and international standards committees: ANSI, CISPR, IEC.
- Characterization of ultrawideband devices for interference study conducted by ITS. This work was vital in understanding potential interference effects of ultrawideband radio and other devices on existing radio services such as GPS, and airport navigation systems. This work was sponsored by OSM and NTIA.
- Robert Johnk became convener of the ANTCAL working group at the June 2000 St. Petersburg meeting of CISPR/A, which will develop site qualification measurement techniques for antenna and compliance test sites. This work will be incorporated into future revisions of CISPR-16.
- Provided numerical modeling support for ANSI working group 1-15.6, which will revise the ANSI C63.5 standard on antenna calibrations.
- Development of measurement methods for product emissions testing above 1 GHz. This work is being done for ANSI working group 1-13.2 on site qualification above 1 GHz.
- Development of ultrawideband chamber qualification tools based on time-domain site attenuation. This method will eliminate cumbersome quasi free-space references required for fully-anechoic chamber testing defined in draft CENELEC and IEC standards.
- Applied new time-domain site attenuation technique to EMC compliance chamber at the Hach Company Chamber in Loveland, Colorado. The new NIST system was successfully used to assess performance improvements after a chamber retrofitting process.
- Used NIST-developed time-domain measurement technology to evaluate the effects of electromagnetic radiation on commercial aircraft. This effort was sponsored by the FAA.
- Completed a feasibility study of the co-conical field generation system. A full turnkey facility development effort will be initiated in the near future. This system will be used as a standard-field generation system for probe calibrations in the frequency range from 10 MHz to 45 GHz. This effort is currently sponsored by the U.S. Air Force.
- Performed precisions calibration of D-Dot sensors used in commercial aviation safety studies. NASA sponsored this effort.
- Measured small samples of hybrid absorber used in commercial EMC testing chambers using a free-space time-domain reflectometer. This work has had a number of industrial sponsors: Lehman Chambers Inc., Hewlett-Packard, Lindgren RF Enclosures Inc, Advanced Electromagnetics Inc., Schaffner EMC, and IBEX/ Panashield.
- Performed in situ measurements of the installed absorber system in a large commercial EMC emissions chamber. This work was sponsored by Lindgren RF Enclosures Inc. "...to offer our support to conduct in situ measurements inside anechoic chambers with time-domain that will later yield digitized data...Lehman Chambers has developed a 3-D Finite-Difference Time-Domain (FDTD) computer modeling program for the design and analysis of anechoic chambers for EMC applications. The work that NIST is intending to do will further validate our techniques and is of extreme interest to us."...Charles Devor, Vice-President, Lehman Chambers, Paul E. Lehman, Inc.
- Assessed the effects of equipment shelters on OATS facilities using time-domain measurement systems. This effort was jointly supported by Storage Technology Inc. and NIST.

" I believe that the experiments planned will be extremely useful to both Storage Tek and to U.S. industry in general."

Monrad Monson,
Senior Compliance Engineer,
Storage Technology Corp.

FY Deliverables

External Recognition

Claude Weil was recognized as an IEEE Fellow, class of 2000, for contribution to microwave metrology.

Recent Publications

R.T. Johnk, D.R. Novotny, and C.M Weil, "Assessing the effects of an OATS shelter: is ANSI C63.7 enough?" IEEE Int. Symp. Digest on Electromagnetic Compatibility, Washington D.C., Aug. 21-25, 2000, pp. 523-528

D.R. Novotny, R.T. Johnk, and A.R. Ondrejka, "Low-cost, broadband absorber measurements," Proc. 22nd AMTA symp., Philadelphia, PA. October 16-20, 1999, pp. 357-362

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D.R. Novotny, R.T. Johnk, and A.R. Ondrejka, "Improved wideband antenna test cell: the co-conical field generation system," Proc. 21st AMTA symp., Monterey, CA. October 3-8, 1999, pp. 144-149

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R.T. Johnk, A.R. Ondrejka, and H.W. Medley, "Low-frequency RF absorber performance with in situ and moveable sample techniques," IEEE Int. Symp. Digest on Electromagnetic Compatibility, Denver CO, Aug. 24-28, 1998, pp. 8-13

A.R. Ondrejka and R.T. Johnk, "Portable calibrator for across-the-road radar systems," Natl. Inst. Stand. Technol. Technical Note 1398, May. 1998

R.T. Johnk, D.R. Novotny, H.W. Medley, A.R. Ondrejka, and C.L. Holloway, "Time- domain site attenuation in low-frequency ferrite-tile chambers," Proc. 21st AMTA symp., Monterey, CA. October 3-8, 1999, pp. 413-421

R.T. Johnk, A.R. Ondrejka, and C.L. Holloway, " Time-domain free-space evaluations of urethane slabs with finite-difference time-domain computer simulations," IEEE Int. Symp. Digest on Electromagnetic Compatibility, Denver CO, Aug. 24-28, 1998, pp. 290-295

Electromagnetic Compatibility

Emissions and Immunity Metrology

Technical Contact:
Galen H. Koepke

Staff-Years:
2.0 professionals
0.5 technicians

Funding Sources:
NIST (60%)
Other (40%)

Parent Program:
Electromagnetic Compatibility

Project Goals

Develop and evaluate reliable measurement standards, test methods, and services to support the electromagnetic compatibility (EMC) needs of U.S. industry. These needs are related to electromagnetic emissions (intentional or unintentional signals transmitted by the test device) and immunity (ability to resist external electromagnetic energy) of electronic devices, components and systems. The characterization of support hardware such as cables, connectors, enclosures, and absorbing or shielding material is an integral part of these measurements. Major challenges are to provide reliable and cost-effective test methods over a large frequency range (10 kHz to 40 GHz and, eventually, higher) and for large test volumes. The efficiencies and uncertainties of EMC measurements directly impact the competitiveness of U.S. manufacturers and the reliability of their products. NIST research quantifies and, in some cases, reduces these measurement uncertainties. NIST expertise, focused on generating and measuring electromagnetic fields, serves as a fundamental resource for industry and government. The main objectives are to ensure harmony and international recognition of US measurements for trade, to provide physically correct test methods, to provide national calibration services, and to serve as an impartial expert body for resolving measurement inconsistencies.

Customer Needs

U.S. industry must evaluate and control electromagnetic interference (EMI) that can impact economics and competitiveness (through trade restrictions and regulations), national security, health, and safety. U.S. industry pays 1 % to 10 % of total product cost and often suffers delays to market while trying to meet various EMC regulations and requirements. Industrial clients for NIST research, development, and measurement procedures are manufacturers of electronic equipment (or any system which employs electronic equipment), and EMI/EMC test and product certification laboratories. Successful completion of this research should result in the development of measurement standards and techniques for EMI and EMC that are meaningful, technically practical, and cost-effective. A reduction in measurement uncertainties will lead to lower product development costs and facilitate acceptance of U.S. measurements by international regulating authorities. NIST, working with industry representatives, can help incorporate these techniques into the standards of both U.S. and international standards organizations. Coordinated international standards based on sound metrology are vital for U.S. industry to participate fully in the global markets for electronic instrumentation and goods.

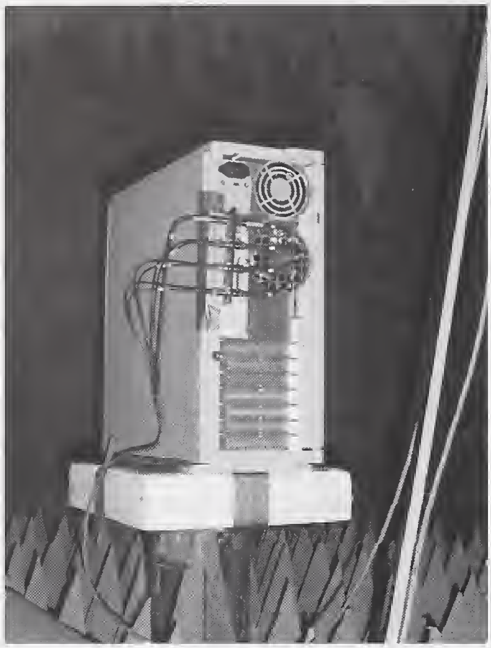
Evaluation of Reverberation Chamber techniques for vehicle EMC testing.

Technical Strategy

Research in EMI/EMC metrology impacts a very broad range of technology and products, including everything from consumer electronics, computers and wireless devices to large vehicles and aircraft. EMI/EMC concerns cover the entire radio-frequency spectrum, necessitating a variety of methodologies and test facilities. NIST research concentrates on developing techniques to generate electromagnetic fields for test and calibrations, to measure fundamental

I am writing to you to express General Motor's interest in the ongoing research conducted by NIST in the area of reverberation chambers. The technical information generated by this research has helped to increase the understanding of the immense capabilities of this technology and has, more importantly, helped to inform the electromagnetic community about the benefits this technology has to offer..."

R. Nelson
Senior Project Engineer
General Motors Corp.



Measuring the radiation characteristics of a typical device-under-test in the NIST anechoic chamber.

electromagnetic parameters in essential segments of the spectrum, and to provide industry with measurement standards and services. The researchers draw on their collective experience in precision antenna measurements, electromagnetic field standards, time- and frequency-domain research, probe and antenna design, modeling and statistical analysis, and instrumentation to develop and analyze EMI / EMC measurement techniques. The techniques often must meet contradictory goals: they must be accurate and thorough, yet practical and cost-effective; they must have a low uncertainty, yet require minimal time.

Facilities for radiated electromagnetic field testing are expensive, and so it is important to fully utilize that investment. NIST researchers examine both the immunity and the emissions measurement capabilities of selected test techniques or facilities. A good example of a technique with a wide range of capabilities including emissions, immunity, and shielding of materials, cables, gaskets, and connectors is the reverberation chamber. NIST research is on the leading edge in the development of reverberation chamber theory and test techniques. Industry and government have accessed this research through conferences and workshops, transaction papers, NIST Technical Notes and reports, special tests and consultations, and NIST participation in committees writing measurement standards. The overall strategy for the EMI/EMC program can be summed up as follows:

Develop and evaluate reliable and cost-effective standards, test methods, and measurement services related to electromagnetic emission and immunity of electronic devices. This includes the critical characteristics of support hardware, such as antennas, cables, connectors, enclosures, and absorbing material. We will continue to focus this research in areas of significant potential benefits and wide applications including reverberation techniques, transverse electromagnetic (TEM) structures, anechoic chambers, time-domain ranges, open area test site (OATS), and new innovative techniques.

MILESTONE: By 2001, develop and evaluate techniques for rapid evaluation/calibration of electromagnetic field sensors (probes) in a reverberation chamber.

MILESTONE: By 2002, develop techniques for characterizing the efficiency and other antenna parameters used as transducers in reverberation chambers and for EMC certification on OATS and semi-anechoic chambers.

MILESTONE: By 2002, develop and propose to standard committee(s) a procedure for measuring the shielding and leakage properties of cables and connectors.

MILESTONE: By 2003, analyze, refine, and optimize measurement procedures for emissions and immunity measurements in a reverberation chamber, publish recommended procedures and applications.

MILESTONE: By 2005, develop and validate efficient methods for the characterization and calibration of measurement facilities using both frequency-domain and time-domain techniques.

MILESTONE: By 2007, develop and validate theoretical and statistical models for the intercomparison of EMI / EMC measurement facilities and procedures.

Most EMI/EMC measurements have large uncertainties due to many sources including insufficient sampling of the radiated fields, poor field uniformity, device-under-test directivity and repeatability, and others. There is often a desire to reduce the number of samples and thereby simplify or shorten the test. While this reduces the cost of the test, it often results in higher uncertainties and, ironically, may require more expensive EMI measures in the product in order to pass emissions or immunity regulations. A careful evaluation of measurement uncertainties can lead to more optimal measurements. This will help to reduce product development and manufacturing costs and increase competitiveness. As the uncertainties are better understood, the credibility of the technique improves and it is easier to gain acceptance of US measurements by International EMI/EMC regulating bodies.

MILESTONE: By 2005, develop and validate statistical models for EMI / EMC testing procedures, and device-under-test directivity and failure distributions. These models, in turn, form a basis for the analysis of total measurement uncertainties.

Provide current research data and other technical inputs to US and international standards development organizations with a goal to harmonize EMI/EMC standards worldwide. We plan to continue our participation on the various IEC, CISPR, ANSI, SAE and IEEE standards committees.

MILESTONE: By 2005, provide technical input and active participation to committees in order to realize the publication of reverberation measurement techniques and TEM structures for EMC applications in national and international standards documents.

Accomplishments

- Refurbished the NIST Open Area Test Site (OATS) and anechoic chamber in preparation for research in antenna and emissions measurement methods and uncertainties. These sites support several programs including antenna calibrations and field standards, probe and antenna development, and EMI/EMC metrology. We are also pursuing plans for future world-class electromagnetic research and measurement facilities.

- Published several new NIST Technical Notes and conference papers covering recent developments in the electromagnetic theory, statistical analysis, modeling, and calibration of reverberation chambers.

- Participated in joint research with US automobile manufacturers and the US Navy to evaluate reverberation techniques for vehicle EMI/EMC testing. The research team tested the research vehicles in multiple facilities including reverberation chambers and semi-anechoic chambers. NIST performed facility calibration measurements, test procedure consultation, and data analysis for this research.

- Developed new measurement methods and hardware to characterize ultra-weak emitters. The presence of ambient noise makes the characterization and detection of weak emitters even more difficult. However, spherical near-field scanning theory has been extended to the case where the emissions of the desired source inside the measurement sphere can be separated from the noise due to undesired sources outside the measurement sphere.

- Characterized electrically small emitters using the intrinsic electric and magnetic dipole moments. These dipole moments are difficult to measure for weak emitters, but a sensitive TEM-cell method has been analyzed and verified experimentally.

- Participated in joint research with the Naval Research Laboratory for EMI/EMC testing of advanced radar transmit/receive modules.

- Transferred technical information to several EMC standards committees (IEC-CISPR, IEC-TC77, RTCA DO-160, and SAE) actively drafting measurement requirements for reverberation techniques.

- Developed statistical models describing typical imperfections and improved the statistical models of the fields encountered in reverberation chambers. After an extensive evaluation of the new reverberation chamber facility at NASA Langley Research Center, we were able to contribute significantly to better understanding of reverberation technology. Several sources of errors occur in determining the field parameters in a reverberation chamber. These include antenna efficiency and other antenna effects, problems with inadequate mixing due to poor paddle design and direct coupling between the antennas, and errors in the formulas used to predict the fields. After completing several billions of measurements in several different reverberation chambers, we have been able to develop new measurement and analysis techniques, significantly improving measurement accuracy and reducing uncertainties. We are now able to discern effects in chamber performance on the order of less than 1 dB.

FY Deliverables

External Recognition

Received Best Symposium Paper Award at the 1999 IEEE EMC Symposium, Seattle WA.

Received Best Symposium Paper Award at the 1997 IEEE EMC Symposium, Austin TX.

Recent Publications

J.M. Ladbury, K. Goldsmith, "Reverberation Chamber Verification Procedures, or, How to Check if Your Chamber Ain't Broke and Suggestions on How to Fix It if It Is," Proc., IEEE EMC Symp., 21-25 August 2000, Washington, DC, pp 17-22

G. Koepke, D. Hill, J. Ladbury, "Directivity of the Test Device in EMC Measurements," Proc., IEEE EMC Symp., 21-25 August 2000, Washington, DC, pp 535-539

Ladbury, J.M.; Koepke, G.H., Reverberation Chamber Relationships: Corrections and Improvements or Three Wrongs Can (Almost) Make a Right, Proc., IEEE EMC Symp., 2-6 August 1999, Seattle WA, pp 1-6

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Koepke, G.H.; Ladbury, J.M., New electric field expressions for EMC testing in a reverberation chamber, Proc., 17th Digital Avionics Systems Conference, 2-6 November 1998, Seattle, WA

Ladbury, J.M.; Koepke, G.H.; Camell, D.G., Evaluation of the NASA Langley Research Center Mode-Stirred Chamber Facility, NIST Technical Note 1508, January 1999, pp. 282

D.A. Hill, Spherical-Wave Characterization of Interior and Exterior Sources, NIST IR 5072, December 1997

Butler, C.M.; Hill, D.A.; Novotny, D.R.; Kanda, M., EMI/EMC Metrology Challenges for Industry: A workshop on measurements, standards, calibrations and accreditation, NIST IR 5068, November 1997

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D.A. Hill, Spatial Correlation Function for Fields in a Reverberation Chamber, IEEE Transactions on EMC, Vol. 37, No. 1, February, 1995

D.A. Hill, D.G. Camell, K.H. Cavcey, and G.H. Koepke, Radiated Emissions and Immunity of Microstrip Transmission Lines: Theory and Measurements, NIST Technical Note 1377, July 1995

Koepke,G.H.; Randa, J., Screen-room Measurements on the NIST Spherical-Dipole Standard Radiator, NIST JRES, Vol. 99, No. 6, pp. 737-749, Nov/Dec 1994

M.L. Crawford, M.T. Ma, J.M. Ladbury, and B.F. Riddle, Measurement and evaluation of a TEM/reverberating chamber, NIST Technical Note 1342, July 1990

January 2001

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